

# Towards Realisation of Spectrum Sharing of Cognitive Radio Networks

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# List of Abbreviations

4G	Fourth Generation Communication
5G	Fifth Communication Generation
AWS	Amazon Web Services
BS	Base Station
CAD	Covariance Absolute value Detector
CBRS	Citizens Broadband Radio Service
CBSD	CBRS Device
CCC	Common Control Channels
CCRN	Conventional (Cellular) Cognitive Radio Network
CCTV	Closed-Circuit TV
CDMA	Code Division Multiple Access
CE	Cognitive Engine
CLSM	Closed Loop Spatial Multiplexing
CogMnet	CRNs Management
CR	Cognitive Radio
CRAHN	Cognitive Radio Ad Hoc Networks
CRNAC	CRNs Admission Control
CSD	Cyclostationary Detection
CSS	Cooperative Spectrum Sensing
DSA	Dynamic Spectrum Access
DSM	Dynamic Spectrum Management
ED	Energy Detector
EVD	Eigen Value based Detector
FC	Fusion Centre
FCC	Federal Communications Commission
FSS	Fixed-Satellite Service
GAA	General Authorized Access

IA	Incumbent Access
IaaS	Infrastructure as a Service
IBS	In Band Sensing
ITU-R	International Telecommunication Union- Radio communication sector
IU	Incumbent User
LocDef	Location based defence
LTE	Long Term Evolution
M2M	Machine to Machine
MCE	Modified Cognitive Engine
MF	Matched Filter
MIMO	Multiple Input Multiple Output
MNCE	Monitor and Coordinator Engine
NoSQL	Non SQL
NTIA	National Telecommunications and Information Administration
OBS	Out Band Sensing
Ofcom	The Office of Communications
OH	Ohio, US State
OSI	Open System Interconnection
PaaS	Platform as a Service
PAL	Priority Access License
Pdf	Power Spectral Function
PN	Primary Network
PU	Primary User
PUEA	Primary User Emulation Attack
PUED	PUEA Deterrent
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RBs	Resource Blocks
RCNC	Reliable Cognitive Network Core

RF	Radio Frequency
RSRQ	Reference Signal Received Quality
SaaS	Software as a Service
SAS	Spectrum Access Systems
SNIR	Interference and Noise Ratio
SQL	Structured Query Language
SSDF	Spectrum Sensing Data Falsification
SU	Secondary User
TVWS	TV White Space
White-Fi	White Fidelity
Wi-Fi	Wireless Fidelity (Comm. Standard)
WiMAX	Worldwide Interoperability for Microwave Access (Comm. Standard)
WRAN	Wireless Regional Area Network
WSN	Wireless Sensor Networks

# List of Symbols

$P_{md}$	Probability of missed detection
$P_{fa}$	Probability of false alarm
$y(n)$	The received signal at SU
$s(n)$	PU or other SUs
$\sigma_s^2$	Transmitted signal mean
$w(n)$	Transmitted signal variance
$\mathcal{H}_0$	Hypothesis indicates that IUs are absent.
$\mathcal{H}_1$	Hypothesis indicates that IUs are present.
$\Gamma$	Test statistics of the received signal
$\lambda$	Spectrum sensing threshold
$\hat{\mathcal{H}}_0$	The sensing decision that the IUs are inactive
$\hat{\mathcal{H}}_1$	The sensing decision that the IUs are active
$P_E$	Probability of Error detection
$\overline{P_{fa}}$	target false alarm probability
$\overline{P_d}$	target detection probability
CDF	Cumulative Distribution Function
$Q(\cdot)$	Complementary CDF
$Q^{-1}(\cdot)$	Inverse of Complementary CDF
$P_d$	Detection Probability
$DB_l$	Database of location $l$ in CogMnet
$BS_{n,l}^x$	Base Station of CRN with sequence “ $n$ ” at the location “ $l$ ”
$NL_{DB_l}$	<i>Networks Locations storage unit in <math>DB_l</math></i>
$Lo_{BS_{n,l}^x}$	<i>Longitude position of <math>BS_{n,l}^x</math></i>
$La_{BS_{n,l}^x}$	<i>Latitude position of <math>BS_{n,l}^x</math></i>
$D_{BS_{n,l}^x}$	<i>Date Status of <math>BS_{n,l}^x</math></i>
$R_{BS_{n,l}^x}$	<i>Communication of <math>BS_{n,l}^x</math></i>

$RT_{DB_l}$	<i>Real-Time storage unit of <math>DB_l</math></i>
$HS_{DB_l}$	<i>Historical Storage unit of <math>DB_l</math></i>
$o^t$	Average occupation measurements (in percentage)
$x^t$	Percentage of spectrum availability measurements
$y_n^t$	Spectrum usage of CRN with sequence “ $n$ ”
$Spec$	Average required spectrum by highest performance CRN
$\psi_n$	expected scalability of a CRN with sequence “ $n$ ”
$\Delta_{PN \text{ scalability}}$	percentage increase of spectrum utilisation of PN
$\Delta_{guard}$	safety guard spectrum factor
$\overline{X}$	The percentage average of spectrum availability measurements
$U$	The number of utilised channels
$V$	The number of evacuated channels
$S$	Number of the suspected channels to verified from PUEA
$ch_s$	A channel needs to be verified from PUEA occurrence.
$fmax_s$	Maximum frequency of the $ch_s$
$fmin_s$	Minimum frequency of the $ch_s$
$utti_s$	Utilisation time of the $ch_s$
$utda_s$	Utilisation date of the $ch_s$
$evti$	Evacuation time of the $ch_s$
$evda$	Evacuation date of the $ch_s$
$E$	Number of the suspected channel for being as an attack
$ch_e$	A suspected channel
$BS_e$	Sequence base station number of suspected channel $ch_e$
$fmax_e$	Maximum frequency of the $ch_e$
$fmin_e$	Minimum frequency of the $ch_e$
$utti_e$	Utilisation time of the $ch_e$
$utda_e$	Utilisation date of the $ch_e$
$A$	Number of Attack channels
$ch_a$	An Attack channel

$fmax_a$	Maximum frequency of the $ch_a$
$fmin_a$	Minimum frequency of the $ch_a$
$utti_a$	Attack time of the $ch_a$
$utda_a$	Attack date of the $ch_a$
$BS_a$	Sequence base station of an attack channel $ch_a$
$R_D$	Dropping Rate
$R_B$	Blocking Rate
$\lambda_{PUS}$	Arrival rates of PUs
$\lambda_{PUEAs}$	Arrival rates of PUEAs
$\lambda_{SUS}$	Arrival rates of SUs
$P_{(md+PUEA)}$	Probabilities of missing detection and PUEAs.



# Abstract

Cognitive radio networks (CRN) have emerged as a promising solution to spectrum shortcoming, thanks to Professor Mitola who coined Cognitive Radios. To enable efficient communications, CRNs need to avoid interference to both Primary (licensee) Users (PUs), and among themselves (called self-coexistence). In this thesis, we focus on self-coexistence issues. Very briefly, the problems are categorised into intentional and unintentional interference. Firstly, unintentional interference includes: 1) *CRNs administration*; 2) *Overcrowded CRNs Situation*; 3) *Missed spectrum detection*; 4) *Inter-cell Interference (ICI)*; and 5) *Inability to model Secondary Users' (SUs) activity*. In intentional interference there is *Primary User Emulation Attack (PUEA)*.

To administer CRN operations (Prob. 1), in our first contribution, we proposed CogMnet, which aims to manage the spectrum sharing of centralised networks. CogMnet divides the country into locations. It then dedicates a real-time database for each location to record CRNs' utilisations in real time, where each database includes three storage units: *Networks locations storage unit*; *Real-time storage unit*; and *Historical storage unit*. To tackle Prob. 2, our second contribution is CRNAC, a network admission control algorithm that aims to calculate the maximum number of CRNs allowed in any location. CRNAC has been tested and evaluated using MATLAB.

To prevent research problems 3, 4, and to tackle research problem (5), our third contribution is RCNC, a new design for an infrastructure-based CRN core. The architecture of RCNC consists of two engines: *Monitor and Coordinator Engine* (MNCE) and *Modified Cognitive Engine* (MCE). Comprehensive simulation scenarios using ICS Designer (by ATDI) have validated some of RCNC's components. In the last contribution, to deter PUEA (the intentional interference type), we developed a PUEA Deterrent (PUED) algorithm capable of detecting PUEAs commission details. PUED must be implemented by a PUEA Identifier Component in the MNCE in RCNC after every spectrum handing off. Therefore, PUED works like a CCTV system. According to criminology, robust CCTV systems have shown a significant prevention of clear visible theft, reducing crime rates by 80%. Therefore, we believe that our algorithm will do the same. Extensive simulations using a Vienna simulator showed the effectiveness of the PUED algorithm in terms of improving CRNs' performance.

# Chapter One: Thesis Introduction

*If we take care in the beginning, the end  
will take of itself.*

*Ken Blanchard*

## 1.1 Introduction

The rapid proliferation of wireless technologies and services has led to a scarcity of available wireless resources. According to the International Telecommunication Union-Radiocommunication sector (ITU-R) there will be a demand for 1280-1720 MHz of extra band in 2020 to fill up the current allocated radio spectrum in wireless networks [1]. Furthermore, the inflexible static spectrum management policies followed by government agencies have led to a critical degree of spectrum underutilisation. Recent spectrum occupancy measurement campaigns have revealed that many allocated spectrum bands are used only in bounded geographical areas or over limited periods of time [2]. Therefore, to alleviate the shortcomings in the spectrum, a Dynamic Spectrum Access (DSA) paradigm has been proposed. The Cognitive Radio (CR) technology was proposed by Mitola in 1999 as a promising approach to implementing DSA, which enables Secondary (unlicensed) users (SUs) to utilise the spectrum on a non-injurious to Primary (licensed) users (PUs) basis [3].

In the context of CR, in order to exploit the Dynamic Spectrum Access (DSA) paradigm, three strategies of spectrum accessing have been proposed: *Overlay*, *Underlay*, and *Hybrid* [4]. Firstly, in the *Overlay* (also in some literature called

Interweave) strategy, the SUs are able to utilise the spectrum band during the absences of PUs [5]. Secondly, for the *Underlay* strategy, SUs are able to share the spectrum even when PUs are active, but need to confine their transmission power below the interference threshold of the PUs [6]. Lastly, *Hybrid* transmission strategy proposes that if PUs return, SUs can switch their transmission mode from interweaves to underlay if and only if the transmission power is still below the interference level of the licensees [7].

To support intelligent and efficient utilisation for the available spectrum, CRN functions are categorised in four main components as follows:

- 1) *Spectrum Sensing*: concerns with detecting the idle channels (spectrum holes) [8].
- 2) *Spectrum Decision*: deals with identifying and selecting the best channels [9].
- 3) *Spectrum Sharing*: Coordinates the access to select channels among SUs [10].
- 4) *Spectrum Mobility*: Administers the adaptation of the transmission parameters in switching to other best available channels in order to maintaining seamless communication during the transition [11].

As CRNs are wireless in nature, they inherit all topologies present in traditional wireless networks, which are classified into: *Infrastructure-based CRN*, and *Distributed* (in most literature known as Ad CRN or Networks (CRAHN)) [12] (see Figure 1.1). Infrastructure-based CRNs are categorised as: **a)** Conventional (or cellular) CRNs (CCRN) (usually referred to as CRN in the literature); **b)** IEEE 802.22 Wireless Regional Area Networks (WRANs) [13]; and **c)** IEEE 802.11 White-Fi Networks [14]. WRAN and White fi networks are proposed to operate on unused portions in TV channels (called TV White Space (TVWS)). On the other hand, CCRNs can utilise any vacant channel in the band 30 kHz to - 300GHz; however, non-permitted bands (e.g. military, security) are excluded [15].

The rest of this chapter is organised as follows. Section 1.2 explains the motivation of this research. Section 1.3 outlines research problems. Section 1.4 describes our research questions. Section 1.5 presents the main aim and objectives of the research. Section 1.6 gives the methodology adopted in this research to tackle the identified challenges. Section 1.7 outlines the organisation and the contributions of the thesis. Finally, Section 1.8 summarises the publications so far arising from this research.

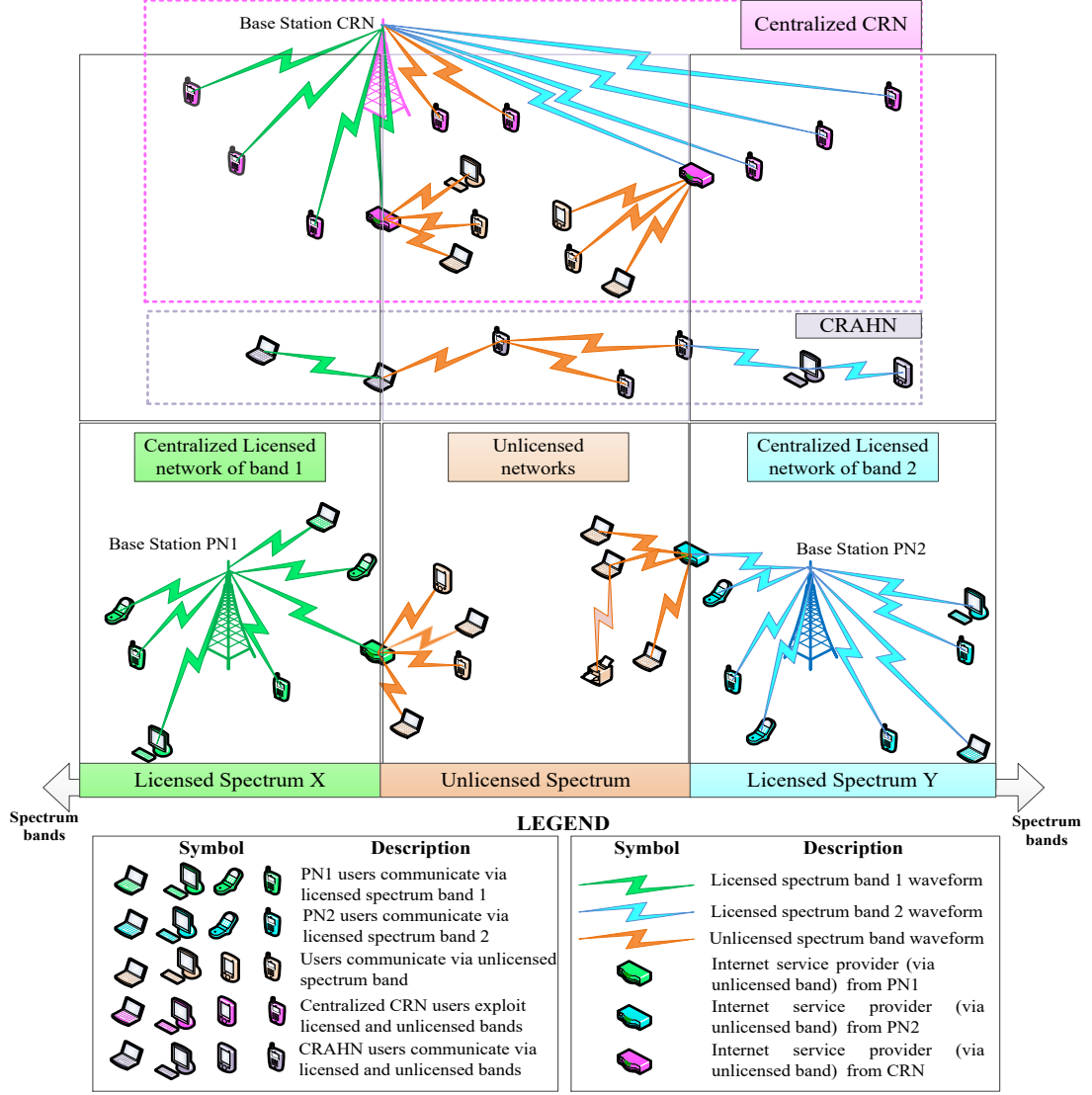


Figure 1.1: Overview of CRNs communications.

## 1.2 Research Motivation

Loss of utilising spectrum bands for CRNs due to other CRNs activities has motivated us to look for potential solutions that will lead to eliminating this challenge. Briefly, to enable efficient communications, CRNs need to address two types of coexistence issues: *Incumbent-coexistence*, and *Self-coexistence*. *Incumbent-coexistence* is related with how to avoid harmful interference with PUs, whereas *Self-coexistence* is concerned with how to prevent interference among overlapping and neighbouring CRNs [16]. Self-coexistence issues trigger CRNs to vacate their under-utilised channels, thinking that PUs have returned to their bands. Therefore, the motivation of this research is tackling self-coexistence issues.

## 1.3 Problems Definition

Missing the opportunity to utilise a free channel by CRN presents a big problem in this kind of networks and a challenge for researchers' society to find a solution. In the literature, numerous research studies have effectively addressed the incumbent coexistence challenges [17] and [18]. In contrast, several critical issues are still open in self-coexistence. This thesis addresses six self-coexistence issues that cause CRNs to lose the opportunity of utilising channels because of other existing CRNs. As depicted in Figure 1.2, the identified issues are as follows:

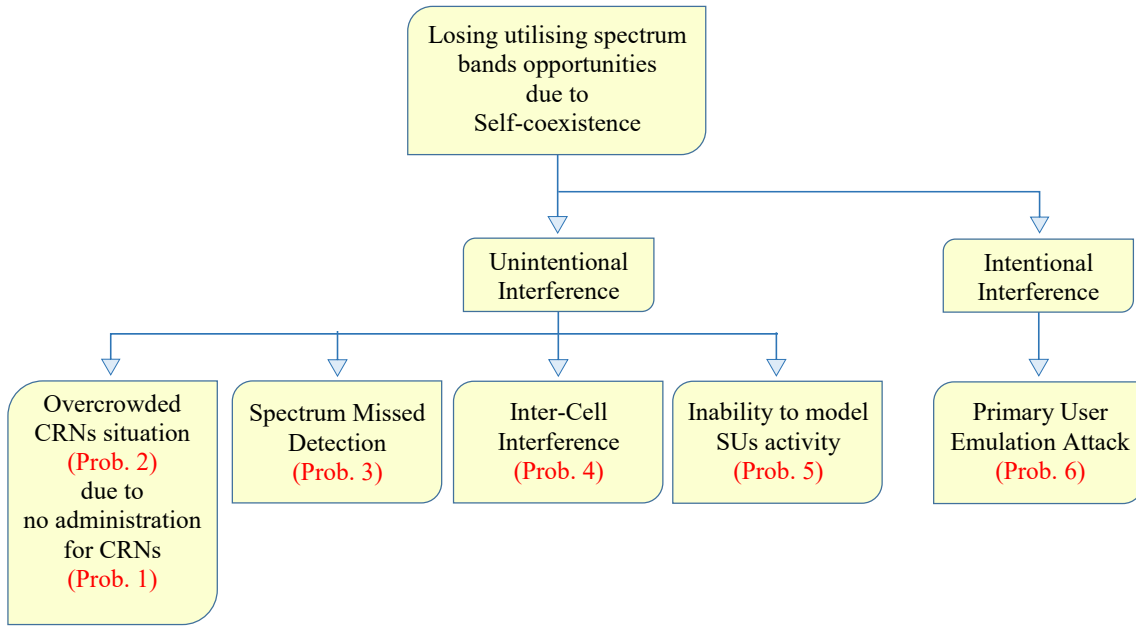


Figure 1.2: Research problem classifications and relations.

### 1.3.1 CRNs Administration

In the literature, a number of internetwork spectrum sharing schemes have been proposed. The most well-known types are: *Geolocation databases* [19], and *Spectrum Access System* [20]. While these two systems are promising, however, both are restricted to a particular band (the first one concerns TV band 56-864MHz, and the latter 3550-3700 MHz) which makes them useless in other bands where CRNs may be eligible to operate. Furthermore, numerous Internetwork sharing frameworks have often been considered the cost (pay to PNs) to benefit (achieve spectrum to CRNs) trade-off (recently surveyed in [21]). Furthermore, they are unable to tackle the following serious challenges (Figure 1.3(a)).

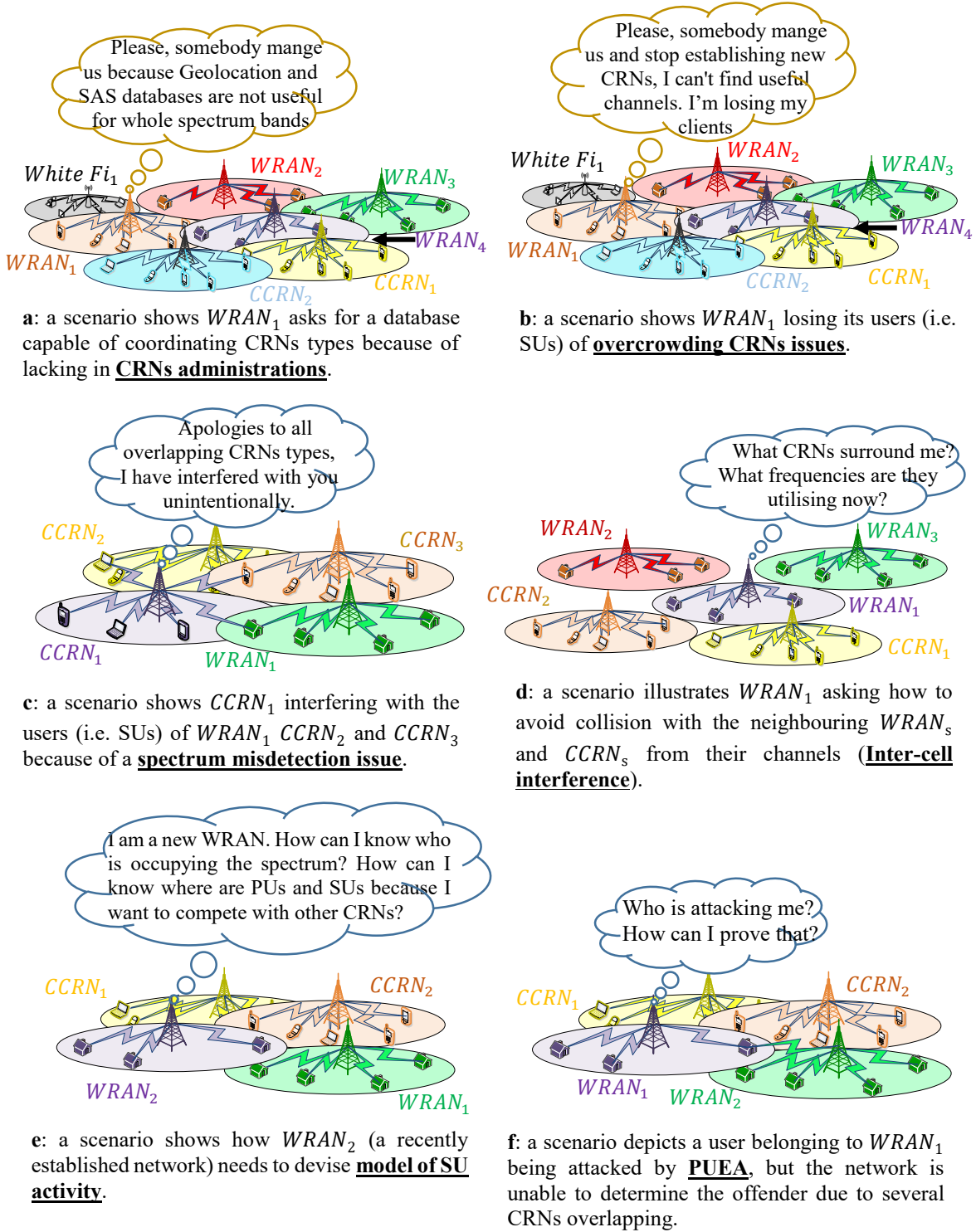


Figure 1.3: The six problems' statements of the research.

### 1.3.2 Overcrowded CRNs Situation

It is expected that when CRNs are implemented, their number and scalability will increase rapidly. Therefore, any uncoordinated increase of the number of CRNs will

rapidly decrease the available spectrum bands, consequently degrading Quality of Service provisioning in existing CRNs. Additionally, the available idle channels have different characteristics, making some of them not exploitable [9]. Additionally, the spectrum measurement campaigns [22]-[34] have shown differences in spectrum occupation from one city to another. Therefore, we believe that it is important to assign the maximum number of operational CRNs in any location to avoid an overcrowding situation. To the best of our knowledge, this important challenge has not been addressed before (see Figure 1.3(b)).

### 1.3.3 Spectrum Misdetection

Spectrum sensing is always imperfect where the error probabilities include false alarms ( $P_{fa}$ ) and missed detections ( $P_{md}$ ). False alarms cause loss of spectrum opportunities by incorrectly detecting an idle channel as busy; whereas the latter lead to interference with both Primary Networks (PNs) and overlapping CRN types. While  $P_{fa}$  affects network performance,  $P_{md}$  will interfere with other overlapping CRNs' transmission, leading them to vacate the apparently occupied channels thinking that the PU has returned [8]. Over the last 15 years, significant spectrum sensing approaches have been proposed to improve detection accuracy: *Algorithms* [35]; *Cooperative strategies* [36]; and *Fusion center rules* [37]. However,  $P_{md}$  is still significant and can reach 0.1, and hence the possibility of interference always exists. This issue is considered as an unintentional interference type. Note that (as will be explained in Chapter Seven) mitigating  $P_{fa}$  will be one of our future tasks (Figure 1.3 (c)).

### 1.3.4 Inter-Cell Interference

Co-channel interference is likely to be caused by re-use of the same frequency bands by other neighbouring CRNs. Similar to the spectrum missed detection problem, this issue falls under unintentional interference types. Several resource reallocation and channel sharing algorithms have been proposed [38]. However, their primary assumption is that all CRNs are willing to exchange their resources information. Additionally, no framework has been proposed to administer the exchanging among all CRN types (conventional CRNs, WRANs, White-Fi networks) (Figure 1.3(d)).

### 1.3.5 Inability to Model SUs Activity

Cognitive Engine (CE) is an intelligent agent that facilitates situation awareness, adaptation, reasoning, learning, and planning [39]. With the anticipated growth in the number of CRNs, it is necessary for each CRN to be aware of other CRNs' behaviour (called SUs activity). This is particularly important for the newly admitted CRNs to devise reliable models for the spectral bands and avoid considering other CRN activities as PUs [40] (see Figure 1.3(e)).

### 1.3.6 Primary User Emulation Attack

As depicted in Figure 1.3(f), Primary User Emulation Attack (PUEA) is a self-coexistence security issue in which a malicious CRN could transmit signals mimicking PUs' signals characteristics to trigger another CRN to vacate its spectral bands [41]. Over the past decade, the PUEA problem has received considerable attention in proposing detection methods in conventional CRN and WRAN. These methods are categorised as *transmitter location verification* and *fingerprint verification* (such as [42] - [45]). However, although the existing schemes are promising on detecting PUEA only, they are not able to prevent CRNs from performing attacks. Therefore, the challenge is in proposing a detecting algorithm that will contribute to deterring the attack. It is worth mentioning that there are several security threats (such as Spectrum Sensing Data Falsification (SSDF)), however, our focus here is how to avoid losing spectrum bands because of other CRNs' spectrum sharing.

## 1.4 Research Questions

In response to the above-mentioned concerns, this thesis seeks to answer the following research questions:

- 1) How can CRNs be administered in such a way that both regulators and CRNs can achieve a number of benefits?
- 2) As long as there is no CRN admission control algorithm in the literature, what rules must be adopted in admitting a new CRN? And how will the networks coverage area be assigned?
- 3) How can spectrum misdetection issues among all CRN types be prevented?



- 4) How can each CRN know exactly all CRN types in its vicinity (existing and those admitted later), and b) how can their under-utilised spectral bands be identified?
- 5) What is the detection method that will contribute to deterring the PUEA issue (i.e. proactive method) rather than merely passively detecting it?
- 6) How could CRNs be able to distinguish between all other CRNs and PUs' activities?

## **1.5 Research Aim and Objectives**

### **1.5.1 Aim**

The aim of this research is to improve the reliability of spectrum sharing of CRNs by addressing critical self-coexistence issues which lead to losing spectrum bands opportunity, thereby preventing deterioration of the Quality of Service (QoS) in CRNs.

### **1.5.2 Objectives**

Our objectives in this thesis are to answer research questions in order to overcome all the problems mentioned in section 1.3. Therefore, they can be summarised as follows:

- 1) Investigate QoS provisioning approaches in CRNs.
- 2) Develop an internetwork framework capable of managing the spectrum sharing of CRNs to tackle research problem 1. It must be designed in such a manner that it can be used as a new environment indication resource.
- 3) Exploit the framework in step (2) to tackle research problem 2 by proposing a CRN admission control algorithm capable of calculating the maximum number of operating CRNs allowed in any location.
- 4) Propose a new CRN core design that exploits the framework in step (2) (in addition to spectrum sensing and geolocation databases) to overcome research problems 3 – 6.
- 5) Exploit new merits in the framework in step 2 to serve as our future work.

## 1.6 Research Methodology

The experimental quantitative methodology is adopted for this research to generate data by hypotheses and experiments followed by extensive simulations and tests. This approach is used in positivist research studies as proposed in [46]. This methodology enables the researchers to follow a number of steps including the definition outline, implementing, processing and evaluating the results. Additionally, constructive comments of the supervisor and conferences and journal reviewers are considered to steer this research. Accordingly, the main phases of our research methodology are shown in Figure 1.4.

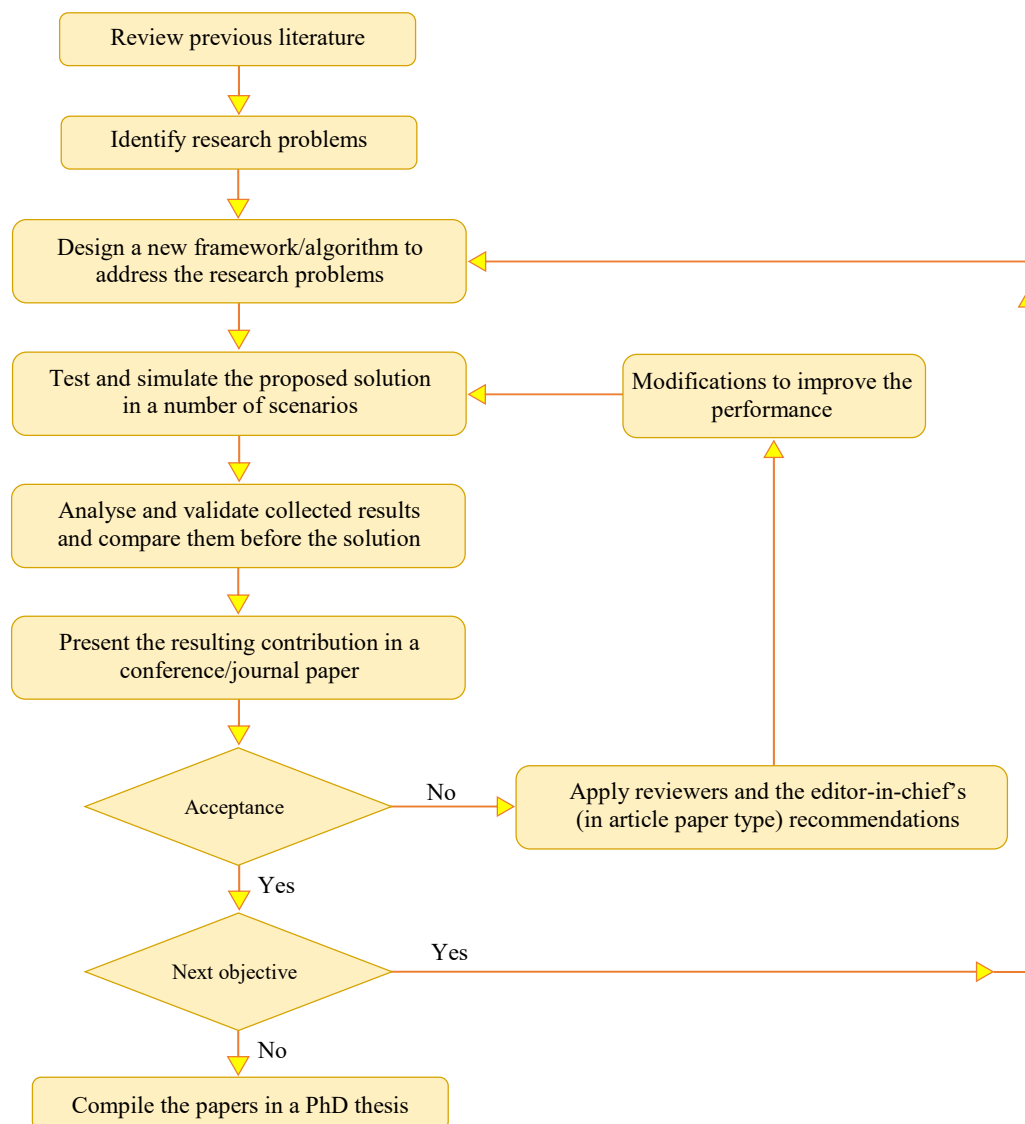


Figure 1.4: Main phases of research methodology.

## 1.7 Contribution to Knowledge

The contributions of this thesis consist of four major parts as follows:

1) CogMnet framework: In this part we presented the CRNs Management (CogMnet) framework that aims to manage spectrum sharing among centralised CRNs. Very briefly, CogMnet coordinates the sharing of CRNs, dividing the whole area into locations, and dedicating a real-time database in each location. The storages of each database are responsible for recording information of CRNs and their under-utilised channels. Based on this, we assigned the main rules that must be followed by CRNs within CogMnet. Accordingly, a number of expected merits can be achieved for both the regulator and CRNs perspective such as: **a)** Assign number of CRNs in any location; **b)** Spectrum misdetection avoidance; **c)** Avoiding Inter-Cell Interference; **d)** Ability to Model SUs Activity; **e)** Obtaining candidate locations for CRNs; **f)** Protection for non-permitted channels; **g)** Sentences against the offending networks; and **h)** New revenue for the regulators.

2) CRNAC algorithm: With the anticipated growth in the number of CRNs, the available spectrum bands will rapidly decrease. Therefore, in the second part of this thesis we proposed a CRNs Admission Control (CRNAC) algorithm that aims to calculate the maximum allowed CRNs in any location. To the best of our knowledge, CRNAC is the first network admission algorithm in a CRN context. Constraints that impact on CRNAC decision were modelled and analysed numerically.

3) RCNC network core design: To demonstrate the effectiveness of CogMnet, in the third part we proposed a new design for infrastructure-based CRNs core, namely, Reliable Cognitive Network Core (RCNC). RCNC utilises and integrates the information of spectrum sensing, geolocation databases, and CogMnet databases. Although RCNC has proposed to prevent spectrum misdetection and inter-cell interference, tackle PUEA, and enabling modelling of SUs activities, a number of components have been proposed that can contribute to improve networks.

4) PUED algorithm: In the last part we proposed a PUEA Deterrent (PUED) algorithm that can provide PUEAs' commission details: offender CRNs and attacks' time and bandwidth. There are many similarities between PUED and Closed-Circuit Television (CCTV) in terms of: deterrence strategy, reason for use, surveillance

characteristics, surveillance outcome, and operation site. According to the criminology literature, robust CCTV systems have shown a significant reduction in visible offences (e.g. vehicle theft), reducing crime rates by 80%. Similarly, PUED will contribute the same effectiveness in deterring PUEAs. Furthermore, providing PUEAs' details will prevent the network's cognitive engine from considering the attacks as real PUs, consequently avoiding devising unreliable spectrum models for the attacked channels. Extensive simulations show the effectiveness of the PUED algorithm in terms of improving CRNs' performance.

## 1.8 Thesis Structure

- Chapter 1: This chapter gives a general overview of the study.
- Chapter 2: The chapter covers the recent relevant works related to our research problems individually. Finally, the chapter discusses how to tackle the identified problems.
- Chapter 3: Here we present the CogMnet framework. Next, we describe the main rules that must be followed by CRNs within CogMnet. After that, the chapter outlines a number of the expected merits of our framework.
- Chapter 4: This chapter proposes CRNAC algorithm. Then, constraints that impact on CRNAC decision were modelled and analysed numerically. At the end, the chapter evaluates the behaviour of CRNAC with numerical results in different scenarios.
- Chapter 5: This chapter presents RCNC architecture. Next, the chapter explains the functionalities the components of RCNC engines. Then, clarifies the time sequence processing of each component. Comprehensive simulation scenarios successfully validate RCNC components.
- In Chapter 6: In this chapter we propose PUED algorithm and describe the mechanism of implementing it. Then we argue how PUED contributes to deterring PUEA commission. Extensive simulations show the effectiveness of the PUED algorithm in terms of improving CRNs' performance.
- Chapter 7 provides concluding remarks and associated future work for this research.

## 1.9 Publications Outcome from this Research

### 1.9.1 Refereed Journals and Conferences Papers

1. M. Fakhrudeen and O. Y. Alani, "Spectrum Improvement in Cognitive Radio Network: Survey," in *Proc. Postgraduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting (PGNet2014)*, Liverpool, UK, June 2014, pp. 119-124.
2. A. Fakhrudeen, and O. Alani, "Reliable Spectrum Sharing Management for Cognitive Radio Networks," in *Proc. of Wireless Innovation Forum Conference on Wireless Communications Technologies and Software Defined Radio (Wlwn Comm '16)*, Reston, VA, USA, March 2016, pp. 49-57.
3. A. Fakhrudeen, and O. Alani, "Comprehensive Survey on Quality of Service Provisioning Approaches in Cognitive Radio Networks: Part One," *International Journal of Wireless Information Networks -Springer*, vol. 20, no. 3, pp. 1-33, April 2017.
4. A. Fakhrudeen, and O. Alani, "Identification as a Deterrent for Security Enhancement in Cognitive Radio Networks," Accepted in *IET Networks* (under publishing stage).
5. A. Fakhrudeen, and O. Alani, "A New Cognitive Radio Networks Core Architecture for Enabling Self-coexistence," *IEEE Access* (under publishing stage).
6. A. Fakhrudeen, and O. Alani, "Comprehensive Survey on Quality of Service Provisioning Approaches in Cognitive Radio Networks: Part Two," *To be submitted to Journal of Wireless Information Networks - Springer*.

### 1.9.2 Posters in Internal Published Conferences Proceeding

1. A poster entitled "Reliable spectrum sharing Management for Cognitive Radio Networks," *Salford Postgraduate Annual Research Conference 2015 (SPARC 2015)*.

2. A poster entitled “Towards Realization of Spectrum Sharing of Centralized Cognitive Radio Networks,” *Salford Postgraduate Annual Research Conference 2016 (SPARC 2016)*.

### **1.9.3 Abstract in Internal Published Conferences Proceeding**

1. A. Fakhrudeen, and O. Alani, “Reliable Spectrum Sharing Management for Cognitive Radio Networks,” *Salford Postgraduate Annual Research Conference 2015 (SPARC 2015)*, May 2015, pp. 81-81.
2. A. Fakhrudeen, and O. Alani, “Towards Realization of Spectrum Sharing of Centralized Cognitive Radio Networks,” *Salford Postgraduate Annual Research Conference 2016 (SPARC 2016)*, May 2016, pp. 111-111.
3. A. Fakhrudeen, and O. Alani, “PUED: A Deterrent Algorithm for Security Enhancement in Cognitive Radio Networks,” *Salford Postgraduate Annual Research Conference 2017 (SPARC 2017)*, June 2017 pp. 43-43.
4. A. Fakhrudeen, and O. Alani, “Reliable Spectrum Sharing Management for Cognitive Radio Networks,” in *Proceedings of the CSE 2016 Annual PGR Symposium 2016 (CSE-PGSym16)*, April 2016, pp. 23-23.
5. A. M. Fakhrudeen and O. Y. Alani, “New Cognitive Radio Networks Core Architecture for Enabling Self-Coexistence,” in *Proceedings of the CSE 2017 Annual PGR Symposium 2017 (CSE-PGSym17)*, Manchester, UK, April 2017, pp. 23-26.

# Chapter Two: Literature Review

*There are no big problems, there are just  
a lot of little problems.*

*Henry Ford*

## 2.1 Introduction

Much interest in CRNs has been raised recently by enabling SUs to utilise the unused portions of the licensed spectrum. CRN utilisation of residual spectrum bands of PNs must avoid any harmful interference with PUs, and prevent interference among CRNs. This coexistence is dependent on four components in CRNs: *Spectrum Sensing*, *Spectrum Decision*, *Spectrum Sharing*, and *Spectrum Mobility*. This chapter comprises two major contributions; firstly, it provides an overview of the development in CRNs and their QoS provisioning approaches. Secondly, it extensively investigates our research problems. The content of this chapter has appeared in the *International Journal of Wireless Information Networks (Springer)* [47] and at an international conference (*PGNet2014*) [10]. Our work is to be followed by the second part of the survey in [48].

The methodology we adopt in this chapter is: Section 2.2 gives an overview on CRNs including applications and classifications of objectives and approaches in Quality of Service provision in CRNs. The following Sections 2.3, 2.4, 2.5, 2.6, 2.7, and 2.8 investigate our research problems' improvements and remaining challenges. Finally, Section 2.9 concludes this chapter with remarks and questions.

## 2.2 Overview on CRNs

### 2.2.1 CRN Applications

Since first proposed by Dr. Joseph Mitola in 1999 [3], CR technology has drawn considerable attention in the research community as the key enabler for significant wireless systems. Most of the study of implementing CR includes:

- 1) Military applications [49].
- 2) CR based Smart Grids [50].
- 3) CR based Sensor Networks [51].
- 4) CR based Femtocells [52].
- 5) CR based Machine to Machine (M2M) communications [53].
- 6) CR for Internet of Things [54].
- 7) Vehicular Networks [55].
- 8) Green Energy Powered CRNs [56].
- 9) CR based Satellite Communications [57].
- 10) Aeronautical Communications [58].
- 11) Disaster Response Networks [59].

Furthermore, the success of CR can be seen in its being adopted as a key technology in fifth generation (5G) wireless communications systems [60]. Moreover, a large number of studies have focused on completing (or advancing in) networks standardisation of IEEE 802.22, 802.11af, 802.15.4, and 802.19.1 [61]. In addition, due to the high demand for extra spectrum, the growth of CR applications is expected to continue to address other modern communications systems.

### 2.2.2 QoS Objectives

Satisfying QoS in any mobile communication system means preserving all the requirements needed by the applications to guarantee a certain level of successful sessions. Similar to any wireless communication network, administrators of CRNs should provide a best possible QoS to the end users. However, QoS provisioning is a more challenging factor in CRNs than in traditional wireless networks [62].



Specifically, QoS must be optimised at the CRN user terminal within intermittent PU and SU (in case of overlapping CRNs) activities without interfering with both PUs' and other SUs' applications. This section explains and introduces the reader to the QoS objectives and the proposed approaches in the CRN literature.

As CRNs are wireless in nature, the QoS objectives of CRNs are similar to traditional mobile networks; however, different techniques and schemes are used due to the nature of undedicated spectrum access. Thus, QoS objectives may be classified into five categories as follows [10]:

- 1) *Throughput*: Defined as the amount of successfully delivered data, as in [63-77].
- 2) *Spectrum efficiency*: Indicates the data rate per frequency band (bit/sec/Hz), such as [78-88].
- 3) *Delay*: Refers to the total time that the data (or packets) have taken from being transmitted till successfully received, as in [89-97].
- 4) *Power consumption*: Denotes the total power consumed by the SU terminal device for communications, such as [98-107].
- 5) *Reliability*: Refers to the performance of the network in completing and starting sessions, as in [108-124].

Furthermore, some of the articles consider two objectives jointly, such as in [125-129]. Moreover, a few papers consider three QoS objectives in the research methodology, such as [102] and [130]. However, all QoS objectives have not been considered together in any research studies. Figure 2.1 illustrates these objectives corresponding to their related sub-objectives. To date, several approaches to improving QoS objectives have been proposed. The next sub-section is dedicated to classifying them according to the network components.

## 2.2.3 QoS Provisioning Approaches in CRNs Components

### 2.2.3.1 Previous Works

Over the past ten years, we have witnessed a tremendous growth in the research by academia and industry on developing CRNs. Each CRN component has received close attention from researchers to address QoS requirements. To assimilate the rapid achievements, it is noticeable that every year several surveys are published on the state

of the art, aiming to address particular points in the CRN context. Indeed, the surveys published in the highest impact factor journals are organised with extensive description and discussion to cover the area that they prepared for. After an extensive search, we found that these surveys could be grouped into seven main categories:

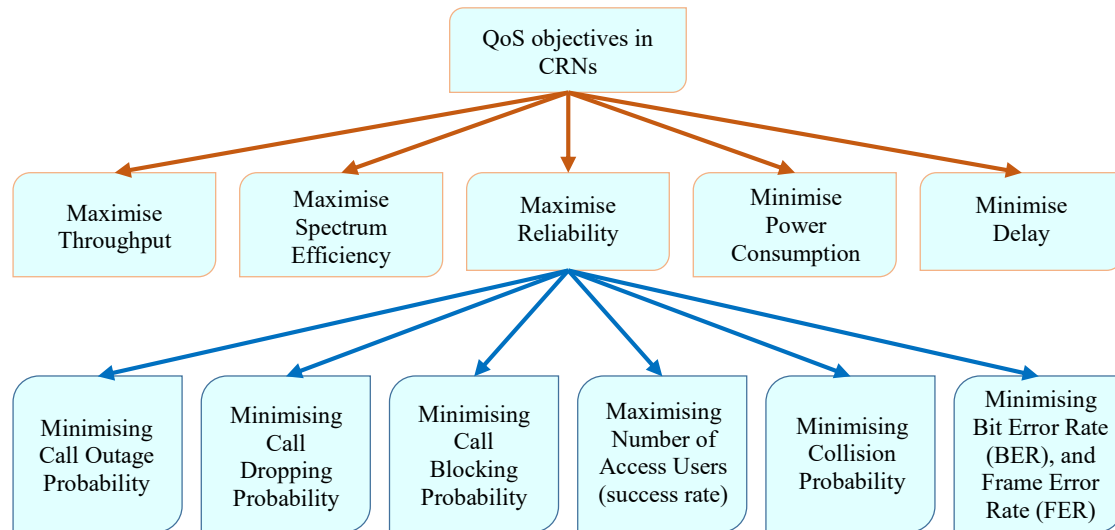


Figure 2.1: Classification of QoS objectives in CRNs.

- 1) Concern on a certain QoS objective, such as [10] & [131].
- 2) Describing the technical development in one CRNs component, as in [9] & [132].
- 3) Extensively explaining a function of a CRN component, as in [2] & [133].
- 4) Clarifying a function rule in all CRN components, such as [12] & [134].
- 5) Investigating various security challenges, as in [135] & [136].
- 6) Presenting the latest developments in a CR based application, as in [49]-[61].
- 7) Covering a layer in the Open System Interconnection (OSI) model, such as [137] & [138].

It is noteworthy that all previous surveys highlighted the advantages and the disadvantages of the existing techniques, algorithms and schemes to improve QoS objectives. To the best of our knowledge, none have presented the approaches adopted to improve QoS objectives in CRNs components.

## 2.2.4 Taxonomy of the Approaches

To describe QoS provisioning approaches in CRNs coexisting components for reliable spectrum sharing among themselves and with PNs, it is necessary here to clarify exactly what is meant by these components. As illustrated in Fig. 2.2, these components as well as their QoS approaches can be explained briefly as follows.

### 2.2.4.1 Spectrum Sensing Component

This refers to detecting the vacant channels to be utilised via Overlay or the bands that are able to be exploited by Underlay strategy [10]. Therefore, it has a crucial impact on CRN performance. According to the CRN literature, the two main QoS provisioning approaches in spectrum sensing stage are:

- 1) Sensing Accuracy.
- 2) Sensing Efficiency.

Furthermore, these two main approaches include several approaches as follows [47]:

- a) Optimizing threshold of detection.
- b) Cooperative sensing.
- c) Multi-stage sensing.
- d) Wideband spectrum sensing.
- e) Adaptive sensing.
- f) Obtaining sensing outcomes from external sources.

It is worth mentioning that several studies have been published on achieving accuracy-efficiency trade off, such as [139].

### 2.2.4.2 Spectrum Decision Component

This concerns selecting the best detected channels according to certain constraints (e.g. channel holding time, channel capacity, and channel SU location) [140]. In this category, QoS provisioning approaches were proposed in the literature as follows [47]:

- 1) Optimising Channel Selection.
- 2) Minimizing Channel Selection Overheads.
- 3) Enabling of Modelling SUs activity.

Indeed the spectrum prediction based on spectrum modelling plays a crucial role in the selection, as in [141].

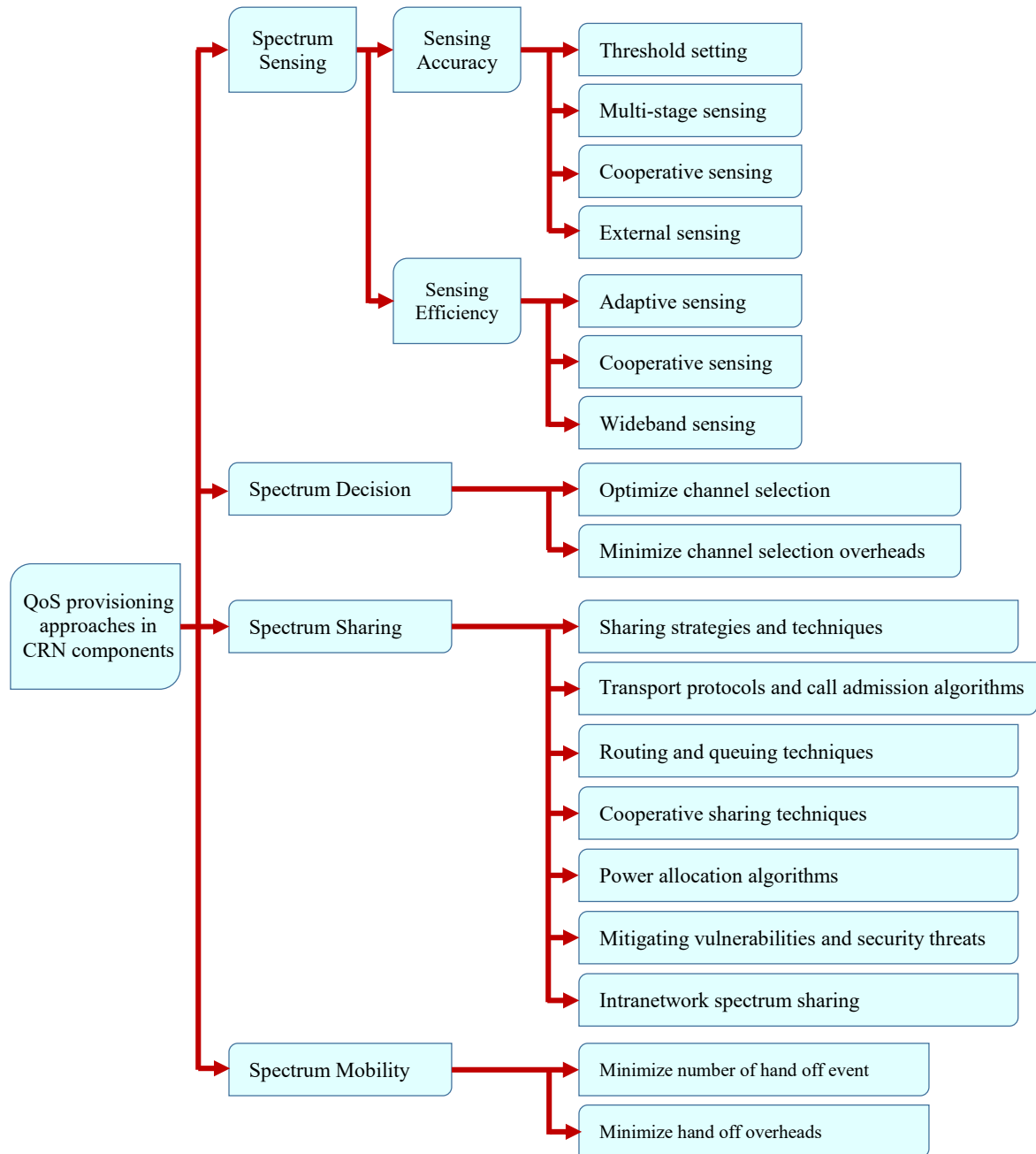


Figure 2.2: QoS Provisioning approaches in CRNs' components.

### 2.2.4.3 Spectrum Sharing Component

The approaches of this component concern accessing the selected bands and adapting transmission parameters accordingly [142]. Therefore, the findings of QoS approaches in this component concern propose:

- 1) Sharing Strategies and Techniques, such as:
  - a) Overlay, Underlay, and Hybrid transmission, as in [71].
  - b) Multiple Input Multiple Output (MIMO) technique (surveyed recently in [18]).
- 2) Transport protocols such as in infrastructure-based CRN [143] and in CRAHNs [144].
- 3) Resource allocation techniques with different admission algorithms (also called Intranetwork spectrum sharing), as in centralised CRNs [51] and in CRAHNs [145].
- 4) Routing and queuing algorithms in CRAHNs, as in [96].
- 5) Cooperative sharing methods, as surveyed recently in [36].
- 6) Power allocation algorithms, as in [76].
- 7) Minimising the security threats and vulnerabilities that may degrade QoS provision of some or all networks, such as PUEA, and Byzantine attack [45].
- 8) Internetwork spectrum sharing frameworks that manage spectrum bands sharing among overlapping CRNs, such as [20].

### 2.2.4.4 Spectrum Mobility Component

Spectrum mobility refers to reconfiguring SUs by evacuating their utilised spectrum bands when PUs are detected and maintaining seamless communications requirements during the transition to other available spectrum bands [146]. This component depends mainly on CRNs' cognitive engine (in case of proactive handing off) and how long a delay the running applications may permit [147]. In other words, spectrum decision and sharing strategies have the main influence on spectrum mobility. According to the CRNs literature, QoS approaches in this component concern:

- 1) Minimising number of hand off events, such as in [148].
- 2) Minimising handoff overheads, as in [149].

## 2.3 Research Problem: Spectrum Missed Detection

### 2.3.1 Introduction to Spectrum Sensing Features

There is a large volume of published studies describing spectrum sensing accuracy and sensing efficiency without clarifying the approaches used. For example surveys such as that conducted in [35] evaluate most sensing types including their capabilities and weaknesses, without highlighting on the QoS provisioning approaches. Spectrum sensing procedures can be described using a hypothesis testing problem that is given in Equation 2.1 [107]:

$$y(n) = \begin{cases} w(n) & \mathcal{H}_0 \\ s(n)h(n) + w(n) & \mathcal{H}_1 \end{cases} \quad (2.1)$$

Where  $y(n)$  is the received signal at SU,  $s(n)$  is PU or other SUs (hence forward referred to as Incumbent User (IU)) transmitted signal with zero mean and variance  $\sigma_s^2$  and  $w(n)$  is a zero-mean Additive White Gaussian Noise (AWGN) with variance  $\sigma_w^2$ .  $h(n)$  denotes the fading channel gain of the sensing channel between SU and IU, and  $\mathcal{H}_0$  represents the hypothesis that IUs are absent, while hypothesis  $\mathcal{H}_1$  indicates that IUs are present. After that SU will compute the test statistics  $\Gamma$  of the received signal and compare it with a predetermined threshold (static threshold approach) ( $\lambda$ ) for each band. Mathematically, the comparison is written as [150].

$$\begin{aligned} \hat{\mathcal{H}}_0: \Gamma &< \lambda \\ \hat{\mathcal{H}}_1: \Gamma &\geq \lambda \end{aligned} \quad (2.2)$$

where  $\hat{\mathcal{H}}_0$  and  $\hat{\mathcal{H}}_1$  indicate the sensing decision that the IUs are inactive and active respectively. IU detection probability  $P_d$  should be high enough to avoid harmful interference with PU; however, two types of detection errors are highly possible, measured in terms of (a) **False alarm probability**  $P_{fa}$ : which is defined as the detector indicating the IU is present while it is absent (i.e.  $Pr\{\hat{\mathcal{H}}_1|\mathcal{H}_0\}$ ); and (b) **Missed detection probability**  $P_{md}$ : which is defined as the detector deciding that the channel is vacant while it is not (i.e.  $Pr\{\hat{\mathcal{H}}_0|\mathcal{H}_1\}$ ). Accordingly, the probability of error detection  $P_E$  can be calculated by the following [108]:

$$P_E = P_{fa} * Pr(\mathcal{H}_0) + P_{md} * Pr(\mathcal{H}_1) \quad (2.3)$$

where  $P_{fa} * Pr(\mathcal{H}_0)$  indicates that IU is absent while the detection device is reporting IU to be present, whereas  $P_{md} * Pr(\mathcal{H}_1)$  denotes that IU is present while the device reports it is not. As illustrated in Figure 2.3, all spectrum sensing components that have been proposed in the literature are summarised briefly as follows:

1) There are two kinds of spectrum sensing in CRN tasks: a) **In Band Sensing (IBS)**: indicates sensing the currently utilised channels; and b) **Out of Band Sensing (OBS)**: refers to sensing unutilised channels to be used in case of handoffs [48].

2) There are two different types of sensing dependency: a) **Internal sensing**: defined as the CRN performs spectrum sensing tasks locally by its users; and b) **External sensing**: indicates obtaining the channels' status from a Wireless Sensor Network (WSN) which may report the outcomes to CRNs for certain fees or databases (spectrum pooling) which act as spectrum brokers between PNs and CRNs [48].

3) There are two spectrum sensing frequency types: a) **Proactive sensing**: defined as periodic sensing of the spectrum; and b) **Reactive sensing**: denotes on-demand sensing that depends on the modelling of the utilised spectrum [148].

4) There are two procedures of spectrum sensing: a) **Cooperative sensing**: refers to collaborating and sharing sensing outcomes by SUs to achieve detection; and b) **Non-cooperative sensing**: indicates that each SU depends on its own sensor to obtain the status of the spectrum (in CRAHNs only) [107].

5) There are three types of detection methods: a) **Transmitter based sensing**: defined as the SU analysing the state of the channel to identify its status; b) **Interference temperature based sensing**: indicates interference strength brought by SU to IU, which can be measured by interference temperature; and c) **Receiver based sensing**: refers to the SU identifying channel status by exploiting the emitted leakage power from a local oscillator of IU RF frontend [146].

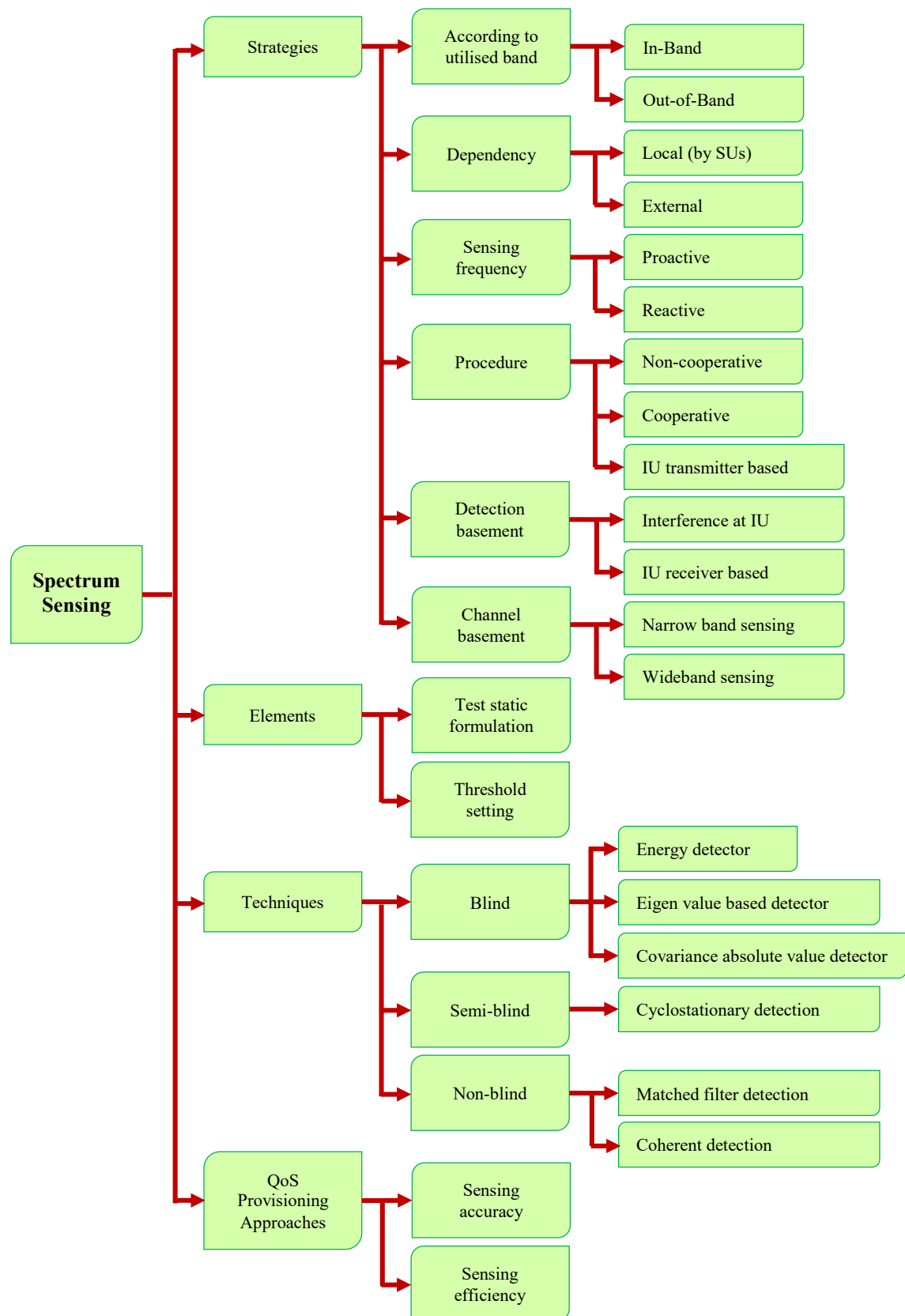


Figure 2.3: Taxonomy of spectrum sensing components in CRN.



6) There are two methods of spectrum bands sensing: a) **Narrow Band Sensing**: refers to SUs performing sensing for a single utilised channel; and b) **Wideband Sensing**: indicates sensing of SUs for multiple channels simultaneously [48].

7) There are two design elements of spectrum sensing: a) **Test statistic**: defined as formulating appropriate modelling of test statistics that may provide reliable information about a channel's occupancy; b) **Threshold setting**: refers to assigning a certain threshold value used to differentiate between the hypotheses  $H_0$  and  $H_1$ , which can be fixed or adaptive [151].

8) There are three types of spectrum sensing techniques: a) **Blind sensing technique**: defined as a detector requiring no information about the received signal, such as *Energy Detector* (ED), *Eigen Value based Detector* (EVD), and *Covariance Absolute value Detector* (CAD); b) **Semi-blind sensing technique**: indicates a detector that needs some prior information about the IU, for example noise power estimation, such as *Cyclostationary Detection* (CSD); and c) **Non-blind sensing techniques**: refers to the detector needing an IU signature as well as noise power estimation, such as *Matched Filter* (MF), and *Coherent detector* [35].

9) There are two main QoS provisioning approaches topics in spectrum sensing: a) **Spectrum sensing accuracy**: defined as the total amount of reliability of detecting spectrum opportunities, where  $P_{md}$ , and  $P_{fa}$  are measurement metrics of the trustworthiness of sensing; and b) **Spectrum sensing efficiency**: defined as the total period (unit of time) that a CRN takes to determine the spectrum opportunities [10].

Finally, efficient detection techniques are pivotal to reducing data transmission interruptions, and to selecting the best channels with a seamless handoff from one band to another [150].

### 2.3.2 Spectrum Sensing Accuracy – Missed Detection Problem

The performance of spectrum sensing in CRN depends on received Signal to Interference and Noise Ratio (SINR). There are four causes of error detection related to SINR, which can be summarized as follows [48]:

- 1) Static threshold setting.
- 2) Low received (SINR), for example, hidden terminal problems.

- 3) SU is in a deep fade from shadowing and multipath.
- 4) Sampling requirements.

The basis of error detection using the energy detection method is best explained in Figure 2.4. Although the figure is not based on any empirical measurement, it enables the reader to understand the error detecting concept. More specifically, Figure 2.4(a) presents utilisation from PUs in a licensed channel, and Figure 2.4(b) depicts perfect energy detection. However, because of the aforementioned four challenges, SU detection may deteriorate, and this starts with error sensing (i.e. false alarms and missed opportunities) as illustrated in Figure 2.4(c). In recent years, much research has been conducted in order to solve and mitigate problems of error sensing. According to the literature, four techniques have been adopted by researchers to improve sensing accuracy. These techniques with their characteristics are as follows:

### 2.3.2.1 Threshold Setting

Traditionally, SU exploits a spectrum sensor of energy or features of IU to determine whether the channels are occupied or not [110]. In ED, the decision threshold  $\lambda$  that distinguishes a channel's status is very important, and this parameter is configured by the system designer. In the literature, optimum  $\lambda$  has been chosen based on: a) *trade-off between  $P_d$  and  $P_{fa}$*  (as shown in Figure 2.5) [152]; and b) *the knowledge of IU signal power as well as noise power* [111]. The IEEE 802.22 working group on WRANs recommended that the target false alarm probability  $\overline{P_{fa}}$ , and target detection probability  $\overline{P_d}$  should be 0.1 and 0.9 respectively [47]. Therefore, the optimal threshold based on each target is calculated as follows [112]:

$$\lambda_{P_d} = \sigma_w^2 \left( \sqrt{\frac{2(2\gamma + 1)}{M}} Q^{-1}(\overline{P_d}) + \gamma + 1 \right) \quad (2.4)$$

$$\lambda_{P_f} = \sigma_w^2 \left( \sqrt{\frac{2}{M}} Q^{-1}(\overline{P_f}) + 1 \right) \quad (2.5)$$

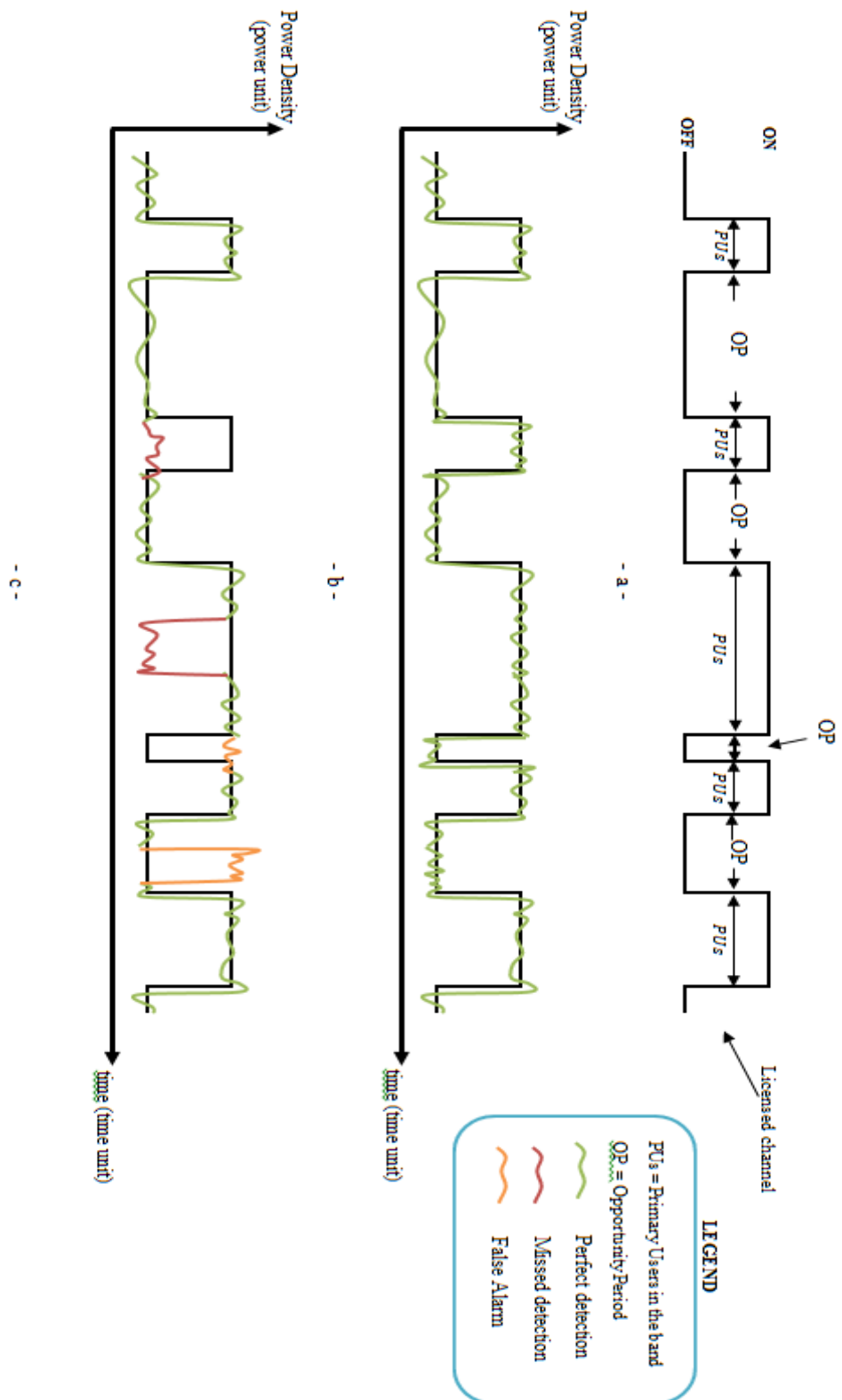


Figure 2.4: Example of error detection probabilities.

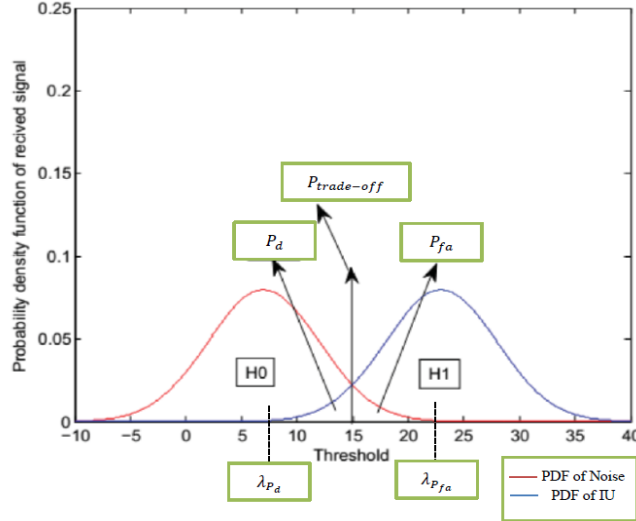
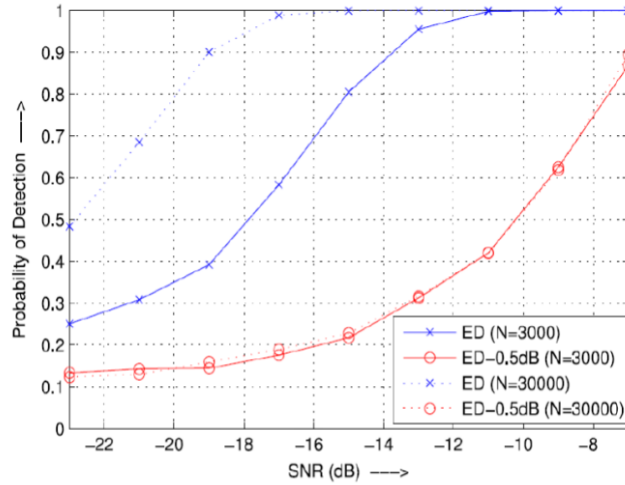


Figure 2.5: Threshold setting (modified from [152]).

Figure 2.6: Performance of  $P_d$  with and without noise uncertainty [37].

where  $M$  is number of samples,  $\gamma$  is Signal to Noise Ratio (SNR) ( $\frac{\sigma_s^2}{\sigma_w^2}$ ), and  $Q^{-1}(\cdot)$  is the inverse of  $Q(\cdot)$  which is a complementary Cumulative Distribution Function (CDF) of a standard Gaussian random variable (i.e.  $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{t^2}{2}\right) dt$ ). As is clear in Equations 2.4 and 2.5, an increase in observed samples increases  $P_d$  and noise uncertainty may decrease it [152]; this fact is illustrated in Figure 2.6. Recently, the authors in [112] proposed a dynamic threshold detection algorithm, where the algorithm proposes two threshold levels for average received PUs energy during a specified observation period. However, the algorithm suffers from computational complexity.

### 2.3.2.2 Multi-Stage Spectrum Sensing

Each spectrum sensing technique has its own cons, for example, ED performance degrades with noise uncertainty (as depicted in Figure 2.6), and CFD consumes power, in addition to a priori information about IU being required. Additionally, the blind techniques suffer from complexity and power consumption. Consequently, each spectrum sensing technique has its own merits and demerits. Thus none of these techniques has an optimal performance in all scenarios [78]. Therefore, dual stage spectrum sensing was proposed in the literature to mitigate the drawback of single stage sensing.

The majority of recent research studies, such as [78], [79], [88], & [98] assume the first stage is ED, but a few studies considered other techniques; for example, the authors in [118] exploited entropy of power spectrum density in the first stage. In the second stage, significant studies such as [98] considered CFD, whereas other studies such as [117] considered EVD as a second stage. More specifically, in the first stage, the observed samples of received signal may be compared with the first threshold  $\lambda_A$  using Equation 2.2; in the case of  $\mathcal{H}_0$ , there is no need to operate the 2<sup>nd</sup> stage, otherwise the second threshold  $\lambda_B$  will be examined. The flowchart of multi-stage spectrum sensing is clarified in Figure 2.7. The first stage is chosen for coarse sensing, while the second stage is considered in fine sensing.

The aforementioned researchers considered optimising spectrum accuracy under constraints and/or QoS objectives. For example, the authors in [78] proposed an optimising scheme of sensing reliability with minimum delay, whereas the authors in [98] optimising spectrum reliability corresponding with minimum energy consumption. However, most articles have drawbacks from different perspectives, such as sensing overheads and complexity, as documented in Table 2.1 and Table 2.2. In the same way, a scheme of three parallel stages of detectors ED, CFD, and MF was proposed in [80] where each detector is used for a certain type of received signal. However, increasing the number of stages may increase the complexity for SUs.

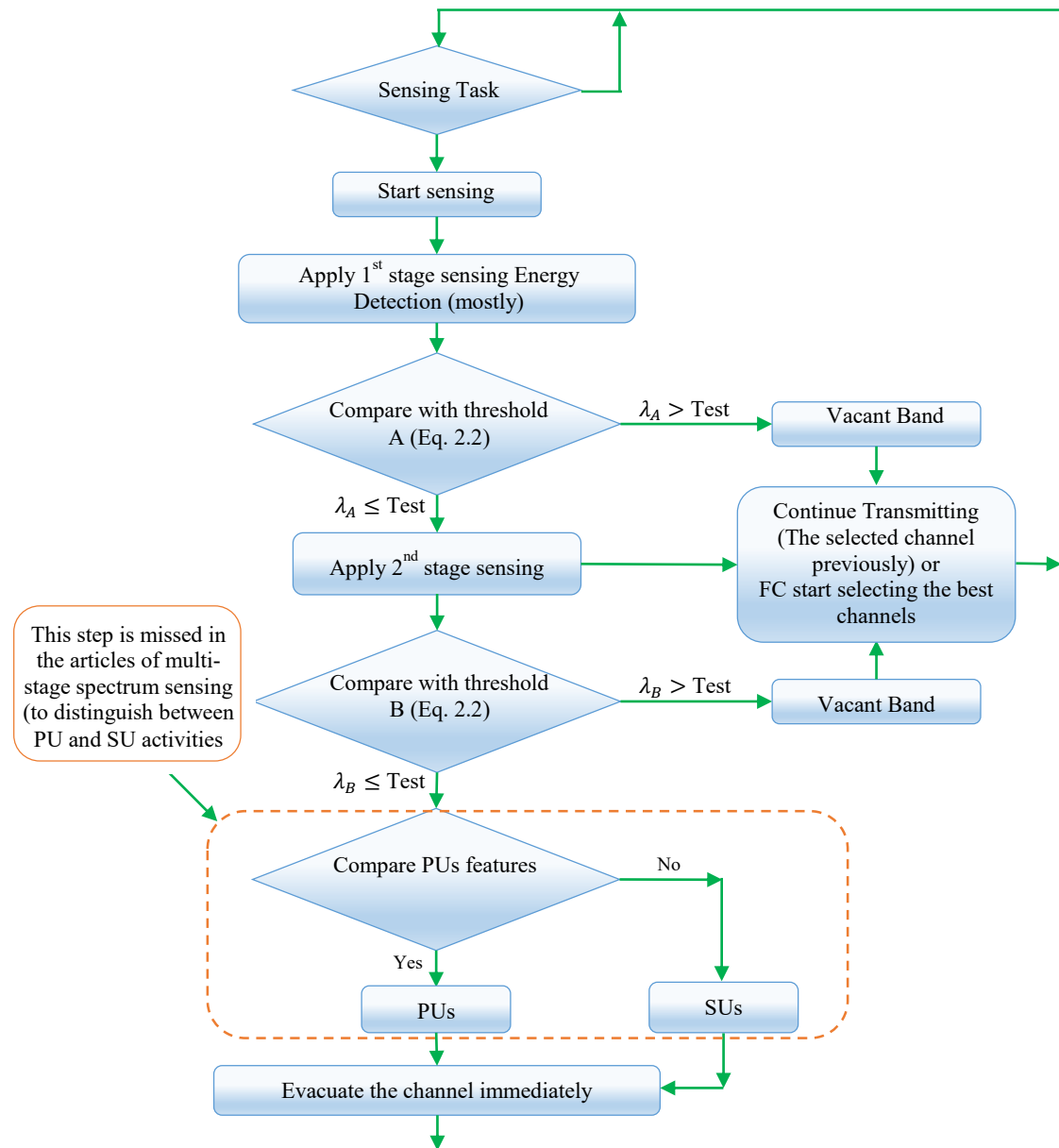


Figure 2.7: The flow chart of multi-stage spectrum sensing algorithms.

Finally, we noticed that a step of distinguishing between PUs and existing SUs was missed in the aforementioned studies. It is believed that distinguishing PUs activity from SUs activity is very important for reliable spectrum modelling; and this step belongs to the spectrum sensing component's responsibilities [48].

Table 2.1: Specifications of multi stage spectrum sensing schemes in sub-section (2.3.2.2).

Reference	Detection techniques						QoS objectives					Cons			
	Energy Detection	Cyclostationary	Maximum Eigenvalue detection	co-variance absolute value	Matched filter detection	Entropy of Power spectrum density	Throughput	Spectrum Efficiency	Delay	Power Consumption	Reliability	Sensing overhead	Required information about PUs	Power consuming	Complexity
[82]	√	-	-	√	-	-	-	√	√	-	√	-	-	-	√
[83]	√√	-	-	-	-	-	-	√	-	-	√	√	-	-	-
[84]	√	√	-	-	-	√	-	√	-	-	√	-	√	√	√
[92]	√√	-	-	-	-	-	-	-	-	-	√	√	-	-	-
[102]	√	√	-	-	-	-	-	-	-	√	√	-	√	-	-
[118]	√	√	-	-	-	-	-	-	-	-	√	-	√	-	-
[119]	√√	-	-	-	-	-	-	-	-	-	√	√	-	-	-
[120]	√	√	-	-	-	-	-	√	-	-	√	-	√	√	-
[121]	√	-	√	-	-	-	-	-	-	-	√	√	-	-	-
[122]	-	-	-	-	-	√√	-	-	-	-	√	√	-	-	√

### 2.3.2.3 Cooperative Spectrum Sensing for Sensing Accuracy

Cooperative Spectrum Sensing (CSS) has been proposed in the literature for gathering detection information from multiple SUs in order to solve the second and third challenges of improving detection accuracy (i.e. hidden terminal detection, and uncertainty due to the SU being in deep fade) [153]. CSS has been extensively studied in the literature: the CSS concept concerns sharing sensing outcomes between SUs (in CRAHNS) or forwarding their local observations to a Fusion Centre (FC) located at the central node or Base Station (BS) (in a centralized CRN) which will make the global decision [36]. For brevity, CSS features can be summarised as follows:

Table 2.2: A summary of QoS objectives and procedures of the researches in subsection (2.3)

			QoS Objectives					Cons						
Ref.	Procedure		CRN Architecture	Throughput	Spectrum efficiency	Delay	Power Consumption	Reliability	Sensing overhead	Complexity	No path loss and fading	Consume power	Only One Licensed Channel	Homogenous channels
[63]	Optimum cooperative grouping		Centralized	√	-	-	√	√	√	-	√	-	-	-
[65]	Sequential two channels sensing		Centralized	√	-	-	-	√	√	√	-	√	-	-
[66]	Sequential Channel Sensing Probing algorithm		Centralized	√	-	-	-	√	-	√	√	-	-	√
[68]	Minimum power consumption at SU at minimum reliability		Centralized	-	-	-	√	√	-	-	√	-	-	-
[70]	Divides SUs into several groups responsible of sensing different channels		CRAHN	-	√	-	-	√	√	√	√	-	-	-
[82]	Cooperative sensing scheme base of faded signal		Centralized	-	√	-	-	√	√	√	-	√	-	-
[83]	adaptive sensing scheme Base on multi-objective GA		Centralized	-	√	-	-	√	-	-	√	-	-	-
[84]	Cluster based two stage fusion stages		Centralized	√	-	-	√	√	√	√	√	-	-	-
[90]	Optimizing sensing period schemes based on different objectives (three schemes)	Maximize throughput	Centralized	√	-	-	-	√	-	-	√	-	√	-
		Minimize Delay	Centralized	-	-	√	-	√	-	-	√	-	√	-
		Trade-off between both schemes	Centralized	√	-	√	-	√	-	-	√	-	√	-
[91]	Efficiency-accuracy trade under of specified constant detection threshold		CRAHN	-	√	-	-	√	-	√	√	-	-	-
[100]	DSM considered both PU status and time-variant multipath channels		CRAHN	-	-	-	-	√	√	√	-	-	-	-
[101]	Sensing regarding recency-based exploration		Centralized	-	√	-	-	√	√	√	√	-	-	-
[102]	Sensing period optimization to achieve minimize power consumption in a diverse cooperative CRN		Centralized	-	-	-	√	√	-	-	√	-	-	-
[126]	Two-phase (coarse and fine) and Two-period (long and short) Spectrum Sensing		Centralized	-	√	-	-	√	√	√	√	√	-	-



1) The proposed methods for CSS in the literature are classified into three categories: a) **All SUs simultaneously**; b) **Certain selected SUs**; and c) **Multi groups (cluster based)**. IEEE recommended CSS to CRN standards IEEE 802.22 WRAN, and it is still in process in IEEE 802.11ah White-Fi [154]. It is worth mentioning that the majority of CSS researchers assumed that the reported channels (i.e. Common Control Channels (CCCs)) are exclusively dedicated among SUs [48].

2) There are two reporting schemes in CSS as follows: a) **Hard CSS**: SUs may report their local decision to the FC; and b) **Soft CSS**: SUs transmit their detection samples (i.e. measurements) to the FC. Clearly, Soft CSS may increase the reliability of decisions; however, it may increase the overheads of transmitting signal samples instead of transmitting one bit decisions [119].

3) There are four decision rules that can be applied at FC which are as follows: a) **AND**: means that all the participated SUs must report the channel as busy (low protection to IUs). b) **OR**: means only one of the SUs reports an occupied channel (high restricted). c) **Majority**: indicates that most participating users consider the channel is occupied. d) **K of N**: means a certain amount (K) of participating SUs (N) report the scanned channel as not vacant (more reliable than the Majority method) [36]. It is worth mentioning that another method of CSS was proposed in the literature, called collaborative CRNs, where several CRNs share their spectrum sensing outcomes to improve their sensing reliability [36]. Additionally, the K of N rule is similar to the OR rule, except that K users from total N users (i.e. SUs) will participate to calculate in decision making. Thus, total  $P_d^T$  and  $P_{fa}^T$  in the FC rules will be as follows [81] & [120]:

a) AND

$$P_y^T = \prod_{i=0}^N P_{y,i} \quad (2.6)$$

b) OR

$$P_y^T = 1 - \prod_{i=0}^N (1 - P_{y,i}) \quad (2.7)$$

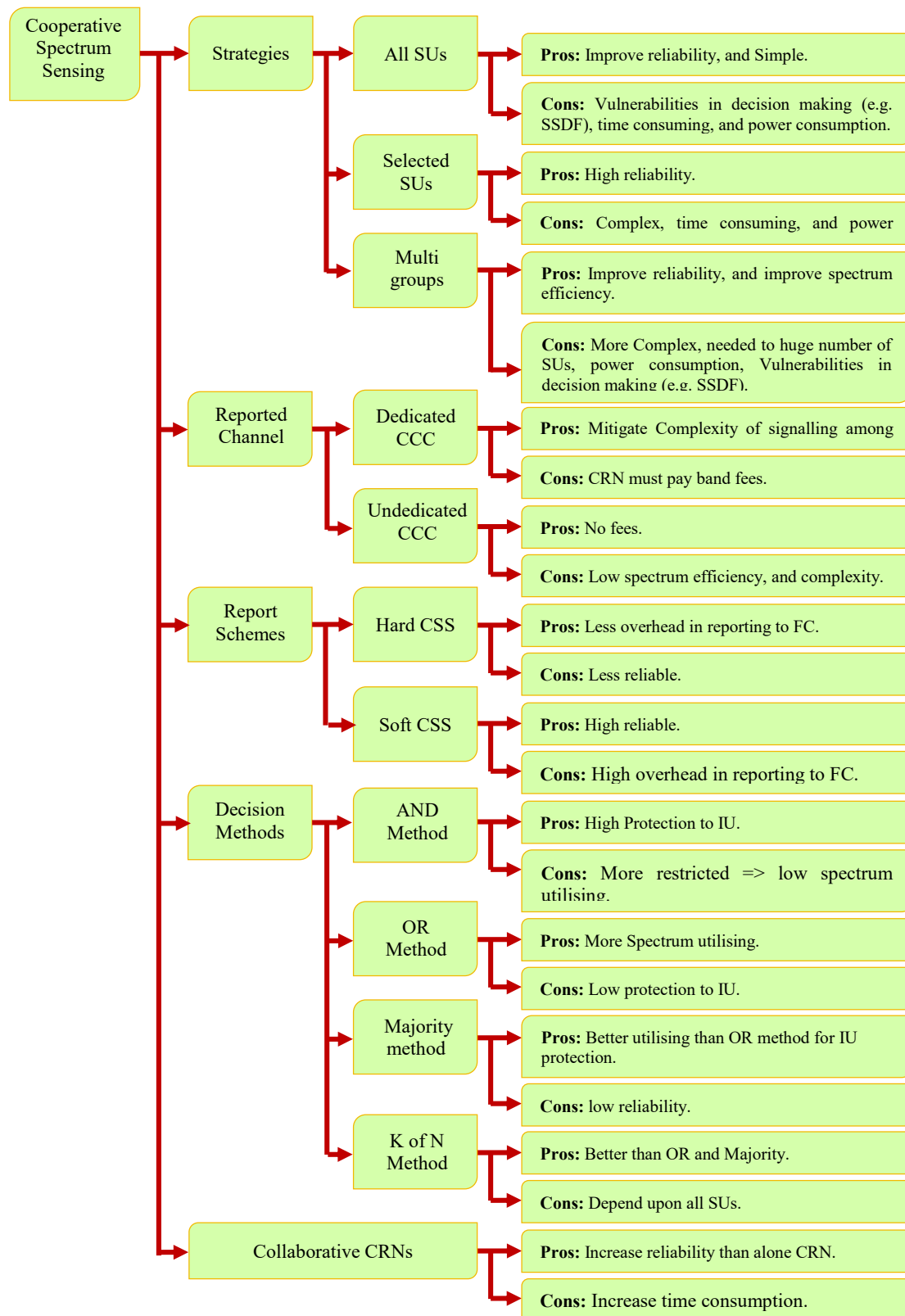


Figure 2.8: Cooperative spectrum sensing features.

c) Majority

$$P_y^T = \sum_{x=\lfloor \frac{N-M}{2} \rfloor}^{N-M} \binom{N-M}{x} P_{y,i}^x (1 - P_{y,i})^{N-M-x} \quad (2.8)$$

A large number of articles have proposed to improve CSS elements, such as maximising energy efficiency in [125], and reliability of CSS in [155]. The main challenge of CSS is reporting false detections from SUs (i.e. SSDF). This problem and other problems will be discussed in the next part of this research on spectrum sharing challenges. Finally, the merits and demerits of cooperative sensing and sharing elements have also been well researched and documented in a recent survey [36], and are summarised in Figure 2.8.

#### 2.3.2.4 External Sensing

This is simply defined as the CRN that exploits the information on vacant channels from an external source [35]. The information should be reported continuously to BSs of all CRNs in order to utilise the best channels in case of handoffs. Generally, external sensing methods can be classified into three categories:

- Sensor nodes belonging to CRN (or other CRNs in case of cooperative CRNs [36]) spread in the coverage area; thereby, CRN architecture constitutes of two networks: A) Sensor Networks, and B) Operational Networks [35].
- External sensor networks may provide details of vacant channels for certain fees [48].
- Spectrum pooling or official databases have the capability of identifying the vacant channels (e.g. TVWS [26], Millimetre wave [156] and Spectrum Access System for the Citizen Broadband Radio Service [20]).

Finally, external sensing may tackle some sensing challenges (explained in the introduction of the current sub-section), and reduce the time required for OBS; thus it will increase spectrum efficiency and throughput, and reduce the delay in offering services. Consequently, since the SUs will not participate in the sensing task, external sensing will reduce the complexity of SU devices [48]. As a comparison, the merits and demerits of external and local sensing from different perspectives are documented in Table 2.3.

Table 2.3: Comparison between local and external spectrum sensing.

Sensing Strategy		QoS Objectives				SU Perspective		Network Administer perspective	
		Reliability	Spectrum efficiency	Time consuming	Power consumption at SU device	Complexity at SU device	Dependency on the number of SUs	Simplify CRN configuration	Additional charge to CRN administer
Local (Internal) sensing	non-cooperative	Low	Low	Low	High	High	No	No	No
	Cooperative	High	High	High	High	High	Yes	No	No
External sensing		Higher	Higher	Low	Low	Low	No	Yes	No

## 2.4 Research Problem: Primary User Emulation Attack

Spectrum sensing is the key challenge in CRNs' coexistence with PUs (incumbent-coexistence) and among themselves (self-coexistence) [157]. As seen in the last section, the last decade has seen the development of efficient sensing methods. However, some vulnerabilities have opened an opportunity for attackers to defeat networks' decision-making processes [135]. One of the most serious issues is known as Primary User Emulation Attack (PUEA), in which a malicious CRN could transmit signals mimicking PUs' signals characteristics to trigger another CRN to vacate its spectral bands (see Figure 2.9). Over the past decade, the PUEA problem has received considerable attention. The existing methods can be classified into two approaches:

- 1) *Defence using Game Theory Strategies.*
- 2) *Detection using verifications.*

### 2.4.1 Defence using Game Theory Strategies.

Game theory strategies have been widely used in resource allocation and cell selection problems in wireless communication networks. Game theory is the study in

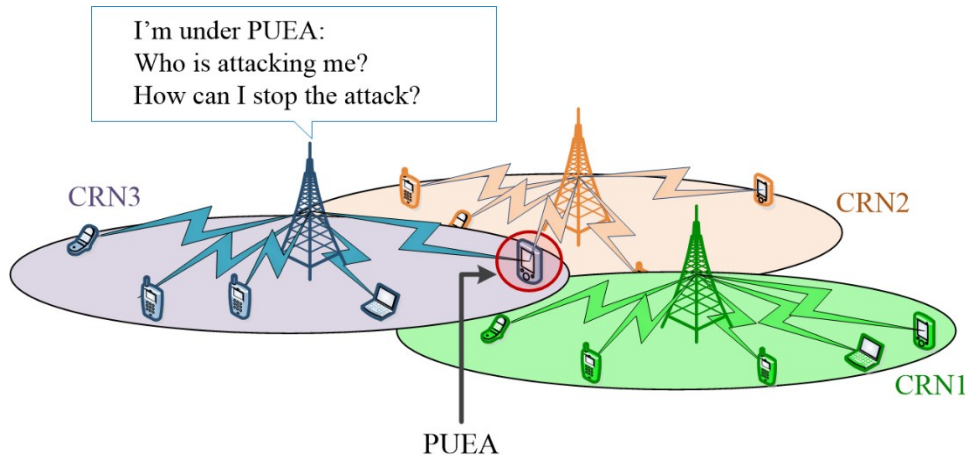


Figure 2.9: An example of three overlapping CRNs, where the base station of CRN2 has mimicked a PU signal to force CRN3 to evacuate one of its communication channels.

mathematical models of the interactions and cooperation among intelligent and rational decision makers, which are SUs in CRNs. The most frequently used types are: Cooperative / Non-cooperative; b) Symmetric / Asymmetric; c) Zero / Non-zero Sum; and d) Simultaneous / Sequential [158]. In the CRNs context, two cooperation games types are used: Bargaining Game and Coalition Game, in which SUs have an agreement on how to fairly and efficiently share the available spectrum bands [159]. In the PUEA topic, the *defence* based methods employ the game-theoretic algorithm to maximise the chance to ‘escape’ from the attackers, such as Extra-sensing games [160], Surveillance Strategies [161], and multistage anti-jamming schemes [162]. However, these methods are not effective for a CRN performing several attacks on different channels simultaneously [163]. Furthermore, who will coordinate the cooperation among CRNs to ensure a reliable spectrum coexistence within the current uncoordinated CRNs situation [48].

## 2.4.2 PUEA Detection Algorithms

An attacker emits spurious signals in the absence of PUs, so that the SUs believe that a PU has returned and thus refrain from using the channel [164]. The detection based approach aims to verify whether the transmitter of the signal is the real PU or not [8]. The existing methods are categorised as:

- 1) Transmitter location verification.
- 2) Fingerprint verification.

In the first type, several schemes based on Received Signal Strength have been proposed, such as [42] and [43]. Specifically, the attacker is identified by comparing the RSS with a predefined real PU signal. Location based defence (LocDef) technique is proposed in [43] and can be applied in the TV band exclusively; the authors assumes that the locations of the TV transmitters are known. To identify PUEA via fingerprint verification, the authors in [44] have proposed a fingerprint check based on phase shift difference, which is unique for each transmitter. Recently, to detect PUEAs, the authors in [45] presented an interesting study that uses cross layer intelligent learning by exploiting channel-tap power. Moreover, a signal activity pattern acquisition and reconstruction System was proposed in [165], which cleverly distinguishes between the signal activities pattern of a real PU and a fake one. Two tests based on exploiting the Power Spectral Function (pdf) of the received signal to detect PUEA were proposed in [164]. However, both tests suffer from being time consuming. Based on a similar idea, Cryptographic and wireless link signature was exploited in [166] to verify the PU signal.

## 2.5 Research Problem: CRNs Administration

In the literature, a number of internetwork spectrum sharing schemes have been proposed. The most well-known types are: *Geolocation databases* [19], and *Spectrum Access System* [20]. Furthermore, numerous Internetwork sharing frameworks have been evaluated on the cost (pay to PNs) to benefit (achieve spectrum to CRNs) trade-off (recently surveyed in [21]).

### 2.5.1 TVWS Geolocation Databases

Currently, organisations such as IEEE and research centres are working towards the standardisation of the CRN operation. In September 2010, the Federal Communications Commission (FCC) released a memorandum opinion and rules for the eliminating of the task of spectrum sensing from unlicensed radio transmitters working on TVWS. As a result, the FCC has paved the way for geo-location databases that are based on channel allocation [167]. These databases would be subject to the entities' fulfilment of and compliance with certain conditions released by the FCC in January 2011 [168]. Consequently, these databases have the capability of identifying the incumbent licensed channels (vacant channels on TV band 56-864MHz only). For example, *Google*

*Spectrum Database* [169], shown in Figure 2.10, shows vacant TV white space spectrum band in the USA. Accordingly, the TVWS users must have the capabilities to access the databases through the internet [170]. However, unused portions of spectrum in the TV band can only be dedicated for new networks. It is very important to point out that when the WRANs are implemented, the TVWS band will not be dedicated to them only. Instead, other CRN types will also be eligible to utilise this band.

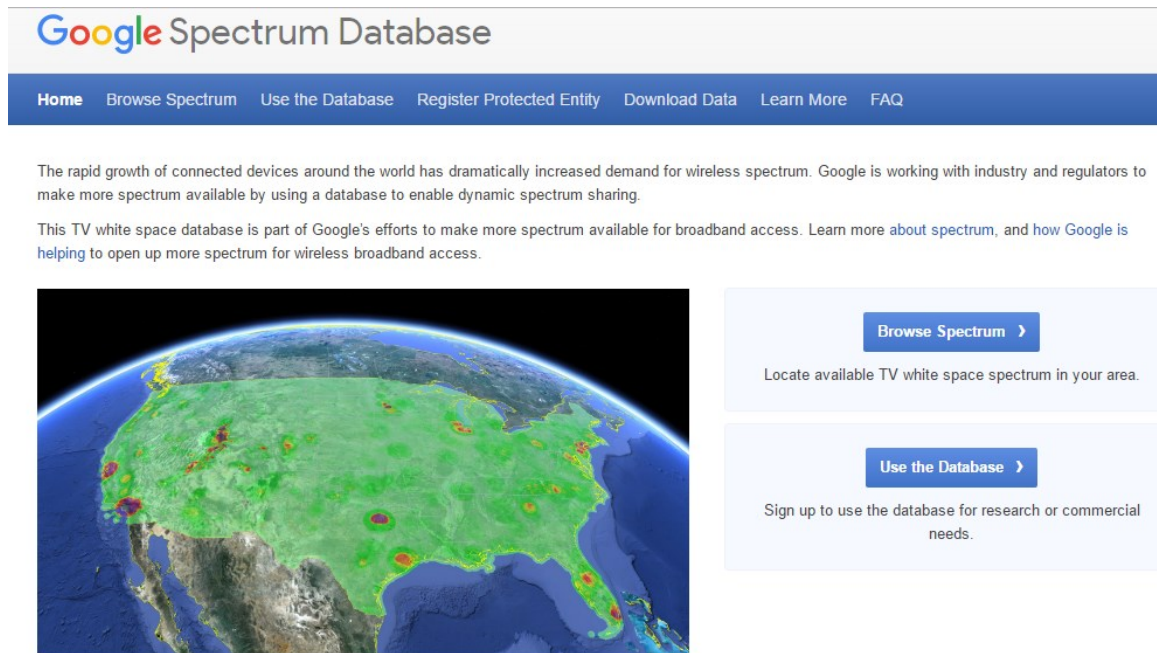


Figure 2.10: Google visualisation of available TV white space spectrum [169].

## 2.5.2 Spectrum Access System

In 2010 the National Telecommunications and Information Administration (NTIA) (an agency of the United States Department of Commerce that serves as the President's principal adviser on telecommunications policies pertaining to the United States' economic and technological advancement and to regulation of the telecommunications industry) identified a number of potential spectrum blocks for spectrum shared access. In particular, the agency released a memorandum to allocate 150 MHz in the 3550-3700 MHz band because the band has limited propagation characteristics and geographically limited incumbent operation [20]. In 2012 the FCC issued a Notice of Proposed Rule Making to create Citizens Broadband Radio Service (CBRS). CBRS will be the first multi-tier spectrum sharing framework, in which one or more Spectrum Access

Systems (SASs) will actively manage incumbents, priority users, and general authorised users [171].

As depicted in Figure 2.11, the three-tier model provides the framework for the proposed Dynamic Spectrum Management (DSM) approach. The first tier, Incumbent Access (IA), includes Primary Federal Incumbents and Grandfathered Fixed-Satellite Service (FSS) Rx-Only Earth Stations. The CBRS would be divided into two tiers: Priority Access License (PAL) and General Authorised Access (GAA). PAL and GAA would be required to operate on a non-interference basis with IA. The FCC also proposed an expanded eligibility for the CBRS where the CBRS Devices (CBSDs) are required to be authorised and coordinated by one or more authorised SASs. Therefore, SAS is the key enabler of the 3.6 GHz spectrum sharing ecosystem that aims to control CBSDs in order to ensure interference free service between CBSDs and Incumbent. SAS usually requests from Tier 2 and Tier 3 devices, then fulfills their requests according to calculations of interference management with incumbents. Therefore, by monitoring incumbents' activity, SAS will reconfigure Tiers 2 and 3 [172].

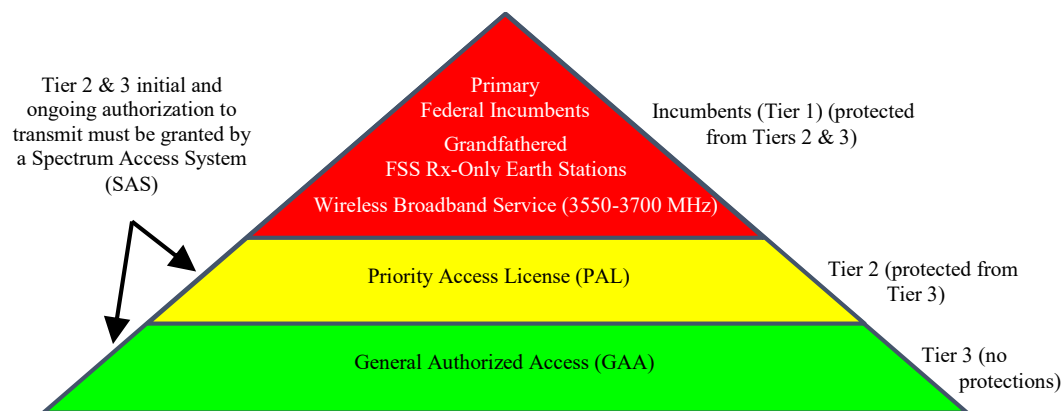


Figure 2.11: Three-tier model framework for the DSM approach in 3.5 GHz [172].

## 2.6 Research Problem: Inter-Cell Interference

Co-channel interference is likely to be caused by re-use of the same frequency bands by other neighbouring CRNs. Similar to the spectrum missed detection problem, this issue falls under unintentional interference types. Several resource reallocation and channel sharing algorithms have been proposed [38]. Specifically, in the literature, two types of resource sharing mechanism are proposed:



- 1) Channel allocation schemes.
- 2) Resource renting.

In the first type, the researchers proposed resource allocation schemes based on either spectrum efficient traffic awareness (e.g. [173]), or minimising interference across the networks (e.g. [174]). The main drawbacks of such spectrum assignment algorithms are that they assume that all BSs (of all CRNs) are willing to exchange their spectrum bands. Additionally, they assume reliable control channels for the networks to exchange their channel information. In the second mechanism (*Resource renting*), the proposed schemes are based on a spectrum pooling concept and consider the cost-benefit trade off. For example, the authors in [175] proposed a spectrum sharing scheme, where each CRN requests an available spectrum from servers located at cloud computing for an unfixed price. The price depends on the channel's properties and number of requested networks.

## 2.7 Research Problem: Overcrowded CRNs Situation

It is reported by the FCC that the spectrum is only 15% - 85% utilised depending on the region, temporal and geographical variations [10]. Furthermore, as investigated in Table 2.4, previous spectrum measurements campaigns have shown that utilisation of the assigned spectrum ranges fluctuates [22]-[34]. Additionally, the available idle channels have different characteristics, making some of them non-exploitable (e.g. (channel holding time, channel capacity, Path loss, Channel switching delay) [9].

For example, Figure 2.12 shows (from *Google Spectrum Database* [169]) on 30 April 2017 the availability of vacant channels in TV white space spectrum band in three states: Washington, Philadelphia, and New York in the USA. Therefore, it is anticipated that when CRNs are implemented, their number and scalability will increase rapidly. Whenever a new CRN is implemented, this means utilising new idle channels; consequently, the number of useful available channels decreases. Accordingly, if this problem arises, the regulators will not be able to stop implementing new CRNs because CRNs are not coordinated and administrated. We believe that it is important to assign the maximum number of operational CRNs in any location to avoid an overcrowding situation. To the best of our knowledge, this important challenge has not been addressed before.

Table 2.4: Most recent spectrum measurement campaigns specifications.

Campaign	City and Country		Frequency Rang (MHz)	Average Duty Cycle (%)	Year of Campaign	Campaign Period (day)
[22]	Kwara State, Nigeria	Rural	50 - 6000	0.18	2016	weekdays
		Urban		5.08		Weekdays
		Urban		1.45		weekends
[23]	San Luis Potosi, Mexico		2401 – 2499	7.00 to 34.00	2016	1
[24]	Dhaka city, Bangladesh		0 – 3000	19.00	2015	1
[25]	Kwara State, Nigeria		48.5 – 880	12.02	2015	1
[26]	Selangor, Malaysia		880 – 960	35.31	2014	1
			1710 – 1880	9.59		
			1885 – 2200	26.08		
			174 – 230	10.92		
			470 – 798	13.36		
[27]	Ruwi, Oman		40 – 3000	13.00	2014	6
[28]	Beijing 1, China		470 - 806	38.00	2014	7
[29]	Kuala Lumpur, Malaysia		470 – 798	27.89	2013	1
[30]	Kampala, Uganda		50 – 1100	37.00	2013	1
[31]	Rio de Janeiro, Brazil		144 – 2690	19.60	2013	90
[32]	San Luis Potosi, Mexico		30 - 910	12.50	2013	1
[33]	Suburb of Pune India		174 - 230	03.55	2013	1
			470 - 806	07.22		
[34]	Hatfield area of Pretoria, South Africa		470 - 854	20.00	2013	42
			935 - 960	92.00		
			1805 - 1880	40.00		

## 2.8 Research Problem: Inability to Model SUs Activity

As mentioned earlier, to achieve both cognitive capability and reconfigurability, CRNs should be aware of the surrounding RF environment, which entails learning from the environment and adapting to environmental variations [47]. In the literature, learning problems are classified into Decision-making and feature classification. While

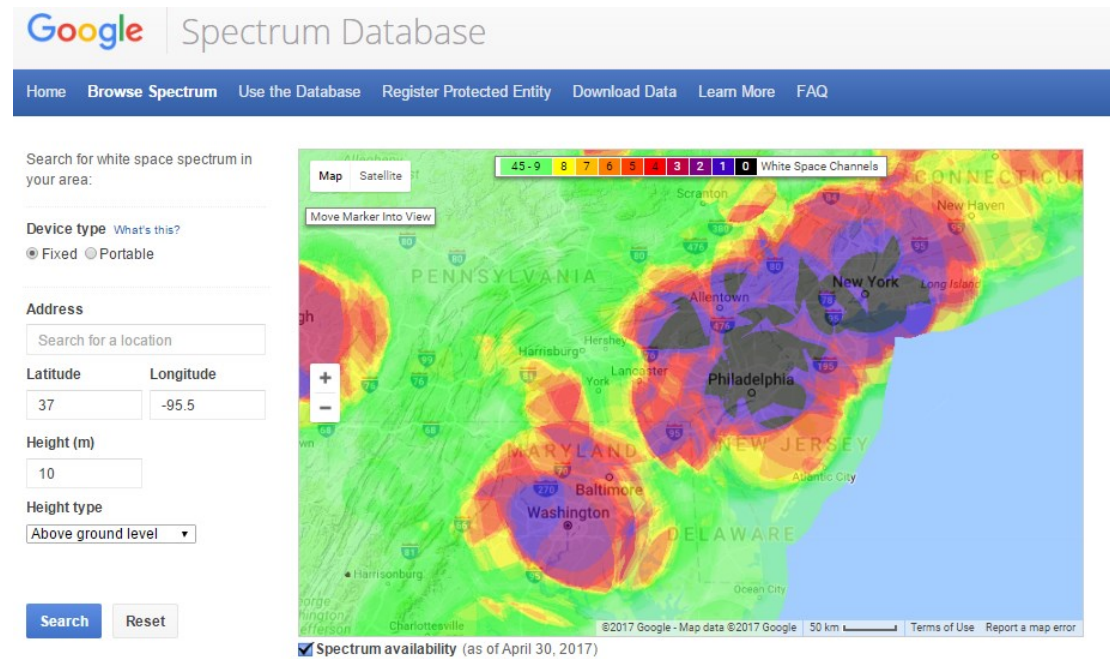


Figure 2.12: TVWS channels availability in three states in the USA - 30 April 2017 [169].

Decision-making involves decision rules and determining policies, feature classification refers to identifying and classifying different observation models [176]. To provide channels' usage patterns, CRNs apply data mining techniques. In the literature, there have been several studies aiming to evaluate the choice of such techniques based on the fact that they are the most popular representatives of different learning paradigms (We refer the reader interested in that topic to the Survey [177]) [178] [179]. For example, the authors in [206] evaluated five data mining techniques (Naïve Bayes, Decision Tree, K-Nearest Neighbour, Support Vector Machine and Artificial Neural Networks) for classification of modulation signals on spectrum sensing.

Therefore, Cognitive Engine (CE) facilitates situation awareness, adaptation, reasoning, learning, and planning highly reliable communication with an efficient spectrum utilisation [44]. It is a key component of CRN distinct from traditional wireless networks. It is the core context of the advanced development of CRN concerning cognitive information stretch and processing with the function of learning, reasoning, planning and decision. Cognitive engine framework is shown as in Figure 2.13, where four elements are multi-domain cognitive, data fusion, learning and reasoning, as well as decision and evaluation [180].

Therefore, using spectrum history is essential to manage opportunistic access in CRNs. However, the CE must be capable of identifying the PUs activities (occupation of PUs) and SUs activity (other overlapping CRNs). Becoming unable to distinguish these activities will lead the CE to devise unreliable models consequently failing to compete for spectrum opportunities with early established CRNs [50]. This problem will have a particularly serious effect on the late admitted CRNs. To the best of our knowledge, there is no method in the literature that enables CRNs to model SUs activity.

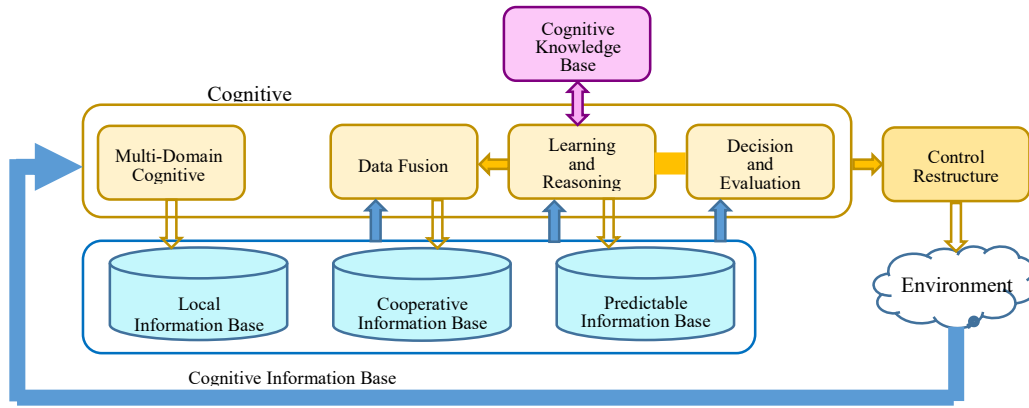


Figure 2.13: Cognitive engine framework [180].

## 2.9 Chapter Summary

This chapter comprised two major contributions. In the first part, we explained more than ten of the most important CR based applications by citing recent overview papers published about each application. We then summarised QoS objectives in CRNs. After an extensive search, we found that most of the previous surveys had highlighted the advantages and the disadvantages of the existing techniques, algorithms and schemes to improve QoS objectives. To the best of our knowledge, no survey has presented the approaches adopted to improve QoS objectives in CRN's components. Therefore, we presented the adopted QoS provisioning approaches in each of CRN's components. To avoid confusing the reader with our main research problem, and due to the extensive nature of the topic, the main part of the surveys is found in [10], [47] and [48].

In the second part, we investigated the impact of CRNs coexisting (intentionally and unintentionally) that may force any CRN to lose utilising spectrum opportunities. We studied the merits and demerits of the studies done to mitigate our research problems.

While the existing solutions are able to some extent to mitigate these challenges, they are unable completely to prevent them. We, therefore, conclude this section with six remarks, each one for a research problem:

1) *Missed spectrum detection*: Despite proposing significant spectrum sensing approaches, algorithms, cooperative strategies, and Fusion center rules, the probability of missed spectrum detection is still significant and can reach 0.1, and hence the possibility of interference always exists.

2) *Primary User Emulation Attack*: While the existing schemes are promising on detecting PUEA, they are not able to provide details of the commission of the PUEA including offender CRNs and attacks' time and bandwidth. Consequently, they are not able to prevent CRNs from performing attacks.

3) *Inter-cell Interference*: Several ideas have been proposed in the literature, all with the primary assumption that all CRNs are willing to exchange their resource information. However, no internetwork spectrum sharing has been proposed to administer the exchanging among all CRN types.

4) *Overcrowded CRNs situation*: There is no doubt that the QoS in any CRN will deteriorate through increasing and fluctuating PUs activities. Furthermore, a rapid growth in the number of CRNs is anticipated, which will lead to a decrease in the available useful spectrum opportunities. Moreover, in the literature, so far no rule has been adopted to assign number of CRNs.

5) *Inability to model SUs activity*: Similar to point 3, with the expected increasing in the number of CRNs, it is necessary for each CRN to be aware of other CRNs' behaviour to devise reliable models for the spectrum. This is very important for CRNs to be able to compete for spectrum opportunities among themselves. However, CRNs are so far still incapable of modelling SUs activity.

6) *CRN administration*: Lastly, while the Geolocation and SAS databases are useful to coordinate CRNs, they are restricted to a particular band which makes them useless in other bands where CRNs may be eligible to operate. Furthermore, these systems are available in only popular countries (e.g. USA).

Finally, after all these studies we have reasons to coordinate all CRNs by certain rules that can contribute to tackling our challenges. Therefore, the next chapter will be our start with a new framework of new managing method for CRNs spectrum sharing.

# Chapter Three: CogMnet Framework

*Knowing where you are going is the first  
step to getting there.*

*Ken Blanchard*

## 3.1 Introduction

Considering the challenges identified, there are good reasons to propose an Internetwork framework capable of regulating the CRNs spectrum sharing. By regulating is meant only coordinating their spectrum sharing rather than licensing spectrum bands to them, because CRNs have no dedicated spectrum bands. Therefore, in this chapter, we present a new internetwork framework called CogMnet. CogMnet is proposed to regulate and coordinate the operation of infrastructure CRNs using real time databases. Unlike conventional frameworks, CogMnet records in real time the transmission parameters of utilised channels of each CRN in a particular database. Each database includes three storage units: Networks Locations storage; Real Time storage; and Historical storage unit. As will be explained later, CogMnet aims to tackle and prevent a number of the self-coexistence issues identified in chapter 2. The content of this chapter has appeared in an international conference in Google Portfolio Event (*Wlnn Comm '16*) [181].

The remainder of this chapter is organised as follows: Section 3.2 presents the architecture of CogMnet, including a description of the system model and the rules that must be followed by each CRN. Section 3.3 gives a general overview of the

requirements that the regulator should prepare for designing CogMnet. In Section 3.4, we summarises both main and emerging merits of CogMnet respectively. Some useful databases for CogMnet are summarised in Section 3.5. Chapter discussion for comparing CogMnet with existing frameworks is explained in Section 3.6. Finally, section 3.7 concludes the chapter.

## 3.2 CogMnet: CRNs Management Framework

CRNs Management (CogMnet) as an internetwork framework that aims to ensure reliable spectrum sharing among centralised CRNs. CogMnet must be administered by a national regulator (or government-approved regulatory which is responsible for spectrum management of wireless systems in the country e.g. Ofcom in the UK ).

### 3.2.1 CogMnet Implementing Procedure

Consider a scenario of multiple centralised CRNs, each consisting of a base station (BS) and related SUs. The communication range of each BS is assigned by its network and may overlap with other CRNs in its vicinity. Spectrum resources that are not being used by the licensed incumbents can be exploited by existing CRNs. We assume that no CRN is able to operate without permission from the regulator (coexistence rules are explained in Section 3.4). Furthermore, the regulator has the exclusive right to stop the operation of any CRN that does not follow CogMnet conditions.

As illustrated in Figure 3.1, CogMnet divides the whole area (i.e., a country) into  $L$  locations and dedicates a real time database  $DB_l$  in each location  $\{l \in L\}$ . The size of the locations must be assigned by the regulator, which may differ from one country to another (e.g. New York state is double the size of the UK and the UK is 21 times larger than Qatar) [182]. Each location  $l$  may contain a different number of CRNs consisting of various cells. Each cell is coordinated by a single base station denoted as  $BS_{n,l}^x$  where "x" refers to the base station sequence in a CRN with sequence "n" at the location "l". Each database  $DB_l$  consists of three storage units to be used as follows:

- 1) *Networks Locations storage unit* ( $NL_{DB_l}$ ): Dedicated to recording CRNs' cells details: a) *Position* (longitude  $Lo_{BS_{n,l}^x}$  and latitude  $La_{BS_{n,l}^x}$ ); b) *Status* (active or not); c) *Date of status* (current status  $D_{BS_{n,l}^x}$ ); and d) *Communication Range* ( $R_{BS_{n,l}^x}$ ).

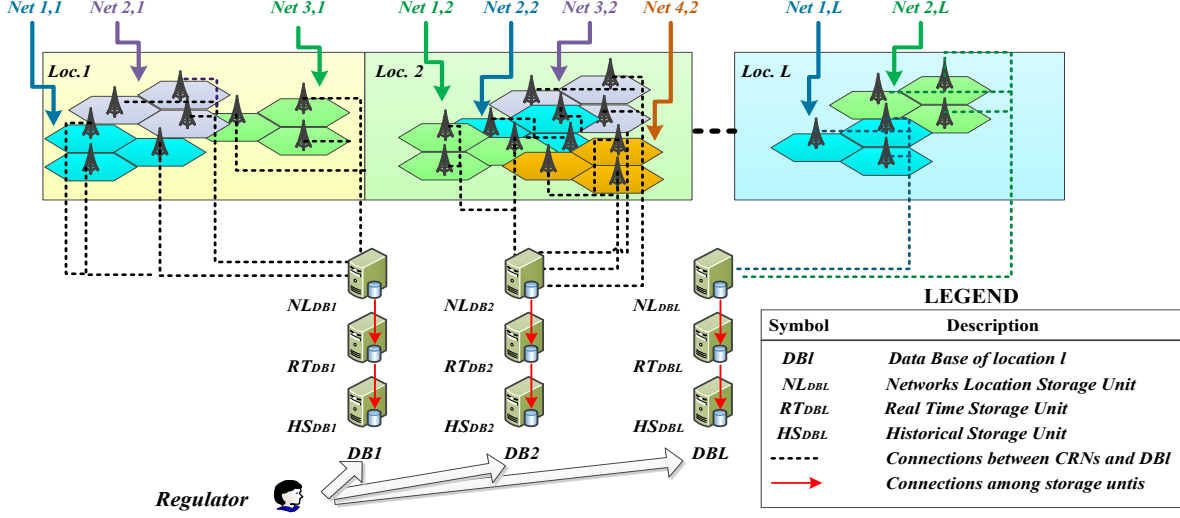


Figure 3.1: CogMnet architecture.

2) *Real-Time storage unit ( $RT_{DB_l}$ )*: Devoted to storing in a real-time the transmission parameters of CRNs' channels. Thereby, each  $BS_{n,l}^x$  sends the following:

- $f_{min}$ , and  $f_{max}$ ;
- Utilisation date and time;
- Modulation and Coding scheme; and
- Transmission power.

3) *Historical Storage unit ( $HS_{DB_l}$ )*: This unit is used to store the details of the vacated channels. Thus, each CRN must send the evacuation time and date of its released spectral bands. Accordingly, the specifications of the evacuated channels will be moved from the  $RT_{DB_l}$  to  $HS_{DB_l}$ .

### 3.2.2 Spectrum Sharing Management Rules in CogMnet

In this sub-section, we suggest certain conditions that all CRNs must follow in exploiting the storage units. The conditions to exploit the databases can be summarised as follows:

#### 3.2.2.1 Mechanism of Informing Channels Details

To ensure a reliable coexistence, regulator will adopt a mechanism that oblige each CRN to send the transmission parameters correctly. Additionally, it must guarantee that the network will send the exact vacation time and period to their databases. This mechanism is beyond the scope of this paper.



### 3.2.2.2 Database inside Network Location

Each CRN can access its location's database (i.e. storage units) in order to obtain information about the bands utilised by other networks. However, to preserve the privacy of the CRNs' utilisation, the access to the storage units must be performed without revealing the identity of the networks. Therefore, the green columns in Tables 3.1, 3.2, and 3.3 are only what can be introduced by existing CRNs. For that reason, each BS has been given a sequence number "**Base Station Sequence in CogMnet**" that does not reflect to which network mat it belongs. Accordingly, if any BS attempted to perform a PUEA on another network, it would be very easy to detect it (as explained in chapter 6).

### 3.2.2.3 Databases outside Network Location

CRNs must be capable of utilising the databases of other locations in order to build a cognitive engine about other locations that the network may plan to extend to. However, in this case, each network must pay an extra fee which depends on the amount of utilised information such as channel utilised in all or part of location, number of base stations, etc.

### 3.2.2.4 Establishing New CRNs

No network can be established without permission from the regulator in order to register its location and utilisations.

### 3.2.2.5 Modifying Existing CRNs

Similarly, the existing CRN must get permission when extending to another location.

### 3.2.2.6 Sentences against the Offending Networks

To achieve reliable spectrum sharing, CogMnet must administer all CRNs including those already existing and those that will be established later. Therefore, there must be penalties paid by any network that attempts to interfere with another one.

Table 3.1: Example of recording form in Networks Locations storage unit  $NL_{DB_4}$  (four CRNs are established in location four).

C R N	Base Station	Base Station Sequence in CogMnet	Longitude	Latitude	Status	Date of status	Communication Range
1	1	1	$Lo_{BS_{1,4}^1}$	$La_{BS_{1,4}^1}$	Active	$D_{BS_{1,4}^1}$	$R_{BS_{1,4}^1}$
	2	2	$Lo_{BS_{1,4}^2}$	$La_{BS_{1,4}^2}$	Inactive	$D_{BS_{1,4}^2}$	$R_{BS_{1,4}^2}$
2	1	3	$Lo_{BS_{2,4}^1}$	$La_{BS_{2,4}^1}$	Active	$D_{BS_{2,4}^1}$	$R_{BS_{2,4}^1}$
3	1	4	$Lo_{BS_{3,4}^1}$	$La_{BS_{3,4}^1}$	Active	$D_{BS_{3,4}^1}$	$R_{BS_{3,4}^1}$
	2	5	$Lo_{BS_{3,4}^2}$	$La_{BS_{3,4}^2}$	Inactive	$D_{BS_{3,4}^2}$	$R_{BS_{3,4}^2}$
4	1	6	$Lo_{BS_{4,4}^1}$	$La_{BS_{4,4}^1}$	Active	$D_{BS_{4,4}^1}$	$R_{BS_{4,4}^1}$

Table 3.2: Example of recording form in Real Time storage unit  $RT_{DB_4}$ .

C R N	Base Station	Base Station Sequence in CogMnet	Channel (MHz)		Utilisation		MCS		Max. Transmit power (watt)
			$f_{min}$	$f_{max}$	Time	Date	Modulation	Code	
1	1	1	680	690	23:59:24:13	12/06/16	16 QAM	1/2	4
3	1	4	2220	2225	23:59:32:26	12/06/16	QPSK	2/3	18
2	1	3	1390	1400	00:00:41:35	13/06/16	BPSK	1/2	20
4	1	6	425	430	00:00:54:24	13/06/16	16 QAM	1/2	4
3	2	5	550	558	00:01:01:27	13/06/16	64 QAM	5/6	4

Table 3.3: Example of recording form in Historical storage unit  $HS_{DB_4}$  (the channel (680-690) MHz is evacuated on 13/06/16 at 00:19:42:34, and the channel (550-558) MHz is evacuated on 13/06/16 at 00:43:48:52).

C R N	Base Station	Base Station Sequence in CogMnet	Channel (MHz)		Utilisation		Evacuation		MCS		Max. Trans. power (watt)
			$f_{min}$	$f_{max}$	Time	Date	Time	Date	Modulation	Code	
1	1	1	680	690	23:59:24:13	12/06/16	00:19:42:34	13/06/16	QPSK	2/3	4
3	2	5	550	558	00:01:01:27	13/06/16	00:43:48:52	13/06/16	64 QAM	5/6	4

### 3.3 CogMnet Implementing Requirements

To design CogMnet properly, it is essential for the regulators to allocate all implementation requirements of CogMnet. Here we list the main requirements that the regulator must prepare.

1) *CogMnet Department*: Create a new department responsible for all CogMnet administration.

2) *Communication engineers*: Assign experts for implementing the CogMnet architecture. For example, make rules for dividing the country into locations and upgrade these rules periodically.

3) *Research Staff*: Dedicate researchers for setting up and implementing CogMnet rules and policy controls. Furthermore for performing a periodic spectrum measurement occupancy campaign, which has a crucial role in assigning the number of CRNs (as we will see later in chapter 4). Moreover, to prepare plans for developing and upgrading CogMnet to meet the aim at all times.

4) *Engineering Technicians*: Use highly skilled workers who are proficient in a programming administrating, and maintaining databases.

5) *Financial Team*: The primary responsibility of this team is supporting each specific area of the financial activities of the CogMnet. This may include the payments for coexisting within CogMnet and exploiting other locations' databases information, and assigning penalty amounts paid by any network that attempts to interfere with another one.

6) *Administrative Staff*: Office administrators work efficiently and productively, ensuring that the administrative activities within CogMnet department run efficiently, including financial planning, CRNs record keeping and billing, and logistics.

7) *Law Staff*: To establish a range of sanctions aimed at deterring the self-coexistence issues. Additionally, to oversee any network that attempts to violate CogMnet rules.

8) *CogMnet Databases*: The regulator must qualify different database operators to provide CogMnet databases. They are responsible for allocating storage size and upgrading according to the location's requirements (in particular Historical storage unit).

## 3.4 CogMnet Expected Contributions

### 3.4.1 Main Merits

#### 3.4.1.1 Maximum Number of Allowed CRNs in any Location

As will be clarified in Chapter 4, based on the suggested rules in CogMnet, the regulators will be capable of assigning a permitted number of CRNs in any location (*second research problem*).

#### 3.4.1.2 Spectrum Misdetection Avoidance

To avoid transmission of more than one CRN on the same channel, CRNs can check the currently utilised spectrum bands in the real time storage unit (on the overlapped BSs) before starting communication (*third research problem*).

#### 3.4.1.3 Avoiding Inter-Cell Interference

By exploiting the real time storage unit in CogMnet, CRNs will be able to avoid reusing channels that are in use in the vicinity (*fourth research problem*).

#### 3.4.1.4 PUEA Prevention

Since all networks utilisations are recorded, it is easy to identify the attacks in terms of attackers, frequencies, time and period and record this information in a report. This report can be used as evidence against the offending network which may contribute to deterring future attacks (*fifth research problem*).

#### 3.4.1.5 Ability to Model SUs Activity

Exploiting the historical storage unit of CogMnet, it will be easy for any CRN to model SUs activity. To the best of our knowledge, this is the first piece of work that enables modelling of SUs' activity. Distinguishing between the activities of PUs and SUs is very important to devise reliable models for spectrum characteristics.

### 3.4.2 Emerging Merits

#### 3.4.2.1 Improving Spectrum Sensing Efficiency

Exploiting the information of real time storage unit before starting to sense may improve sensing efficiency by removing currently utilised channels from sensing. For

example, if the network uses a filter-bank wide band detection technique in [183], then the number of operated filters (for detection) will be reduced, consequently reducing power consumption (*research issue for future work*).

#### **3.4.2.2 Candidate Locations for CRNs**

Any CRN will be able to analyse the utilisations in the historical storage unit of non-overlapping base stations in order to make a list of candidate areas (inside the network location) where the network may plan to operate. The same procedure can be performed for outside network locations by exploiting the information in the databases of other locations.

#### **3.4.2.3 Further Protection of Non-Permitted Channels**

The regulators can utilise CogMnet to guarantee that no CRN will utilise the non-permitted channels (e.g. military, and security bands).

#### **3.4.2.4 New Revenue for Regulators**

Coordinating CogMnet will guarantee a new income to the regulator because all CRNs will pay a certain fee for being within CogMnet. These fees will be insignificant in comparison to guaranteeing reliable spectrum sharing without self-coexistence issues.

#### **3.4.2.5 CRNs Security**

Since all CRNs' coverage area will be known to regulators, they will thereby ensure that the CRNs cannot be utilised by malicious groups. Since it is impossible to detect any CRN operation (because it transmits in non-predefined bands); CRN must be kept secure from any aggressive group. Additionally, the regulator now is capable of stopping the operation of CRNs for any terrorist attack situations in a certain place.

### **3.5 Useful Databases for CogMnet Implementation**

Here we list very briefly the main the most widely used cloud databases in the world which are useful to implement CogMnet. These databases are as follows.

### 3.5.1 Microsoft Azure

Microsoft Azure is a cloud computing service developed by Microsoft. It is generally used for building, and managing applications through a global network of Microsoft managed data centres. It covers different services, such as Development, computing, mobile services, storage services, data management, media services, etc. Furthermore, it provides software as a service (SaaS), platform as a service (PaaS) and infrastructure as a service (IaaS). Moreover, Microsoft Azure supports many different programming languages, tools and frameworks, including both Microsoft-specific and third-party software and systems. Finally, Microsoft Azure is generally available in 34 regions (including UK south and UK west) around the world [184].

### 3.5.2 Amazon Web Services

Amazon Web Services (AWS) has a number of cloud-based database services, which includes both NoSQL (No Structured Query Language) and relational databases. Therefore, it offers a wide range of database services to adapt to the requirements of a variety of customers. These database services are fully managed and can be launched in minutes with just a few clicks. AWS database services include: Amazon Relational Database Service, Amazon Aurora, Amazon DynamoDB, Amazon Redshift, and Amazon ElastiCache. AWS also provides the AWS Database Migration Service, a service which makes it easy and inexpensive to migrate users' databases to AWS cloud. In AWS, the customer can replace paying to purchase software licenses, servers, or leasing facilities by paying only for what the customer is using and for the period as he/she needs, in other words, paying for the services on an 'as used and needed' basis [185].

### 3.5.3 Google Cloud SQL

Google's cloud database services fall into two major categories: Google Cloud SQL and Google BigQuery. The first is a MySQL-like fully relational database infrastructure. On the other hand, Google BigQuery is an analysis tool for running queries on large data sets stored in its cloud [186].

### 3.5.4 EnterpriseDB

EnterpriseDB, a privately held company based in Massachusetts, provides software and services based on the open-source database PostgreSQL. It focuses on the open source PostgreSQL databases. By using EnterpriseDB's Postgres Plus Advanced Server, organisations can use applications written for on-premise Oracle databases through EnterpriseDB [187].

### 3.5.5 Redis Labs

Redis Labs (or Garantia Data) is a private computer software company based in Mountain View, California. It provides a database management system marketed as NoSQL as open source software or as a service using cloud computing. Using Garantia's software allows for automatic configuration of these open source data platforms by helping developers scale nodes, create clusters and architect for fault tolerance [188].

### 3.5.6 Rackspace

Rackspace's database comes in either a cloud or managed hosted offering via Cloud Databases. Rackspace emphasises the container-based virtualization of its Cloud Databases, which, it says, allow for higher performance of the database service compared to being run entirely on virtualized infrastructure. Recently, Rackspace announced a NoSQL database in its cloud from provider Cloudant [189].

### 3.5.7 MongoLab

MongoLab gives customers the access to MongoDB on a variety of major cloud providers, including AWS, Azure and Joyent. Like other gateway-type services, MongoLab also integrates with various PaaS tools at the application tier. MongoLab runs on either shared or dedicated environments, with the latter being slightly more expensive [190].

### 3.5.8 StormDB

Unlike other databases in the cloud, StormDB runs its fully distributed, relational database on bare-metal servers, meaning there is no virtualization of machines. StormDB officials claim this leads to better performance and easier management

because users do not have to choose the size of virtual machine instances their database runs on. Despite running on bare metal, customers do share clusters of servers, although StormDB promises isolation among customer databases. StormDB also automatically shards databases in its cloud. The company is currently in a free beta [191].

## 3.6 Chapter Discussion: CogMnet vs. Existing Related works

### 3.6.1 CRNs within CogMnet

We believe that CogMnet will play important roles towards realisation of spectrum sharing of centralised CRNs. We now describe the possible expected merits of CogMnet.

### 3.6.2 CogMnet: A New Environment Status Indicator

As depicted in Figure 3.2, CRN will have three environment status resources rather than two.

- 1) *The Spectrum Sensing Component*: detects both idle and occupied channels inside the network coverage area. However, it is not perfect.
- 2) *Geolocation Databases*: provide idle channels inside and outside the network location; however, this is restricted to TV bands only, and they are not available in all countries.
- 3) *CogMnet databases*: provide details of the occupied channels inside and outside network coverage area.

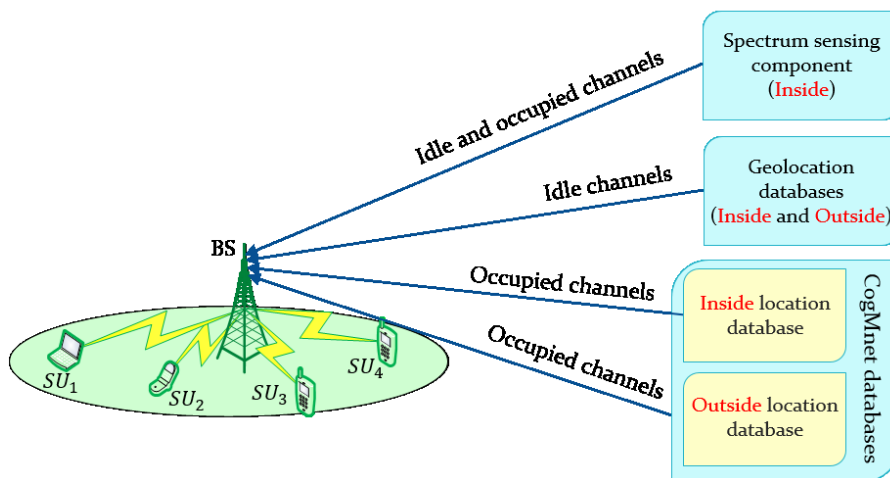


Figure 3.2: CRNs' environment resources after implementing of CogMnet.



Accordingly, by comparing CogMnet with Geolocation databases and SAS systems, we summarise in Table 3.4 the capabilities of each system to tackle self-coexistence challenges. Finally, in this section, we argue the expected merits that need to be validated, which will be our aim in the remaining chapters.

Table 3.4: Comparison of the expected contributions of CogMnet with SAS and Geolocation database.

No.	Merits	Geolocation Database	SAS Databases	CogMnet Databases
1.	Calculate maximum number of CRNs	<i>X</i>	<i>X</i>	√
2.	Deterring PUEA	<i>X</i>	<i>X</i>	√
3.	Protection of Non-permitted channels	<i>X</i>	<i>X</i>	√
4.	Avoiding Misdetected Spectrum issue among CRNs	<i>X</i>	<i>X</i>	√
5.	Tackle Inter-cell interference	<i>X</i>	<i>X</i>	√
6.	Enabling the modelling of SUs activity	<i>X</i>	<i>X</i>	√
7.	Offer idle channels information	√ TVWS band only	√ (3550-3700 MHz) band only	<i>X</i>

### 3.7 Chapter Summary

In this chapter, for a reliable spectrum sharing without self-coexistence issues, an internetwork framework, namely CogMnet, was proposed. Unlike conventional frameworks, CogMnet records in real time the utilised spectrum from the existing CRNs. Therefore, CogMnet is capable of treating challenges such as PUEA, spectrum misdetection, inter-cell interference, etc. Furthermore, it contributes to preventing degradation of CRNs' performance in an overcrowded CRNs scenario. Nevertheless, it is very important for the administration issues of CogMnet to be verified, which cannot be calculated by academic researchers; instead, they need to be calculated either by official regulators or technology companies. Finally, from the description of CogMnet thus far, we conclude this chapter with two remarks:

- 1) The regulators need careful design and implementation.
- 2) CRNs' core design must be changed in order to utilise the new environment resource.

# Chapter Four: CRNAC Algorithm

*Education is the most powerful weapon  
which you can use to change the world.*

*Nelson Mandela*

## 4.1 Introduction

With the anticipated growth in the number of CRNs, the useful available spectrum bands will rapidly decrease. As a result, there will be degradation in QoS provision of the existing networks. This chapter presents a CRN Admission Control (CRNAC) algorithm capable of determining the maximum number of CRNs allowed in any location. Several constraints that impact on CRNAC decisions are modelled and analysed numerically. Additionally, we here argue that correct selection of CRNAC constraints will ensure that there are sufficient spectrum bands available for the newly admitted CRNs in addition to the existing ones. Therefore, CRNAC demonstrates the effectiveness of the CogMnet framework. The content of this chapter has appeared in an international conference (*Wlnn Comm '16*) [181]. It should be noted that, since we aim to address the self-coexistence problems by resource management at **network level** rather than **user-level**, the metric used to measure networks performance is total utilised spectrum bands.

The chapter proceeds as follows. Section 4.2 presents the architecture of CogMnet including a description of the system model and the preliminaries to apply the CRNAC algorithm. The Admission constraints and procedure of CRNAC are explained in Section 4.3. Section 4.4 evaluates the behaviour of CRNAC with numerical results in different scenarios. In Section 4.5 we conduct simulation experiments to evaluate an infrastructure-based CRN in a saturated spectrum situation. We conclude the chapter in Section 4.6.

## 4.2 Preliminaries to Applying CRNAC

As CogMnet is intended to be administered by an official regulator, CRNAC must be applied by the regulators. In this section, we explain the important measurements that the regulator should prepare before starting to implement CRNAC.

### 4.2.1 System Model

Before delving into the important steps needed to start implementing CRNAC, we note that the system model of CogMnet divides the country into  $L$  locations, each consisting of a different number of infrastructure-based CRNs denoted as  $Net_{n,l}$  where  $(n)$  is any network established in location  $(l)$ . In CogMnet, the location  $(l)$  is coordinated via database  $(DB_l)$  that contains the three storages  $(NL_{DB_l}, RT_{DB_l}, \text{ and } HS_{DB_l})$ . However, since the algorithm can be applied in any location, we consider that  $L = 1$ . Therefore, by omitting the metric  $l$ , the database of CogMnet and its storages will be denoted as  $DB, NL_{DB}, RT_{DB}, \text{ and } HS_{DB}$  respectively.

### 4.2.2 Steps before Implementing CRNAC

The regulator should periodically perform two major spectrum measurements:

- 1) Measure spectrum occupancy in order to calculate total spectrum availability.
- 2) Calculate the spectrum utilised by each CRN.

It is important to mention that the time period of measuring spectrum occupancy depends on the regulator's perspectives which may differ from one country to another. Therefore, this time is outside our research scope.

#### 4.2.2.1 Spectrum Measurements Campaigns

In the first set of measurements, the regulator should perform several campaigns to measure spectrum occupancy (occupied by both PNs and CRNs). The measurements should cover the suitable frequency range for CRN operation (e.g. 30MHz to 3GHz as usually assumed in the literature). Thus, assuming the average occupation measurements (in percentage) of one campaign are  $O = \{o^1, o^2, \dots, o^t, \dots, o^T\}$  where  $\{o^t \in \mathbb{R}^+: 0 \leq o^t \leq 100\}$ ,  $\{t \in \mathbb{Z}^+, 0 \leq t \leq T\}$  and  $T$  is the total unit time of one campaign, the percentage of spectrum availability measurements can be defined as  $X = \{x^1, x^2, \dots, x^t, \dots, x^T\}$ , where  $\{x^t \in \mathbb{R}^+: 0 \leq x^t \leq 100\}$  and  $x^t = 100 - o^t$ . Finally, to achieve a more reliable decision, we suggest that the campaign must be repeated  $D$  times.

#### 4.2.2.2 CRNs Spectrum Usage

While measuring  $X$ , the regulator exploits the CogMnet database (the Historical Storage unit) to perform the second set of measurements. These measurements include calculating the percentage of spectrum usage in the same frequency range by each CRN  $Y_n = \{y_n^1, y_n^2, \dots, y_n^t, \dots, y_n^T\}$ , where  $\{Y_n \in \mathbb{R}^+: 0 \leq y_n^t \leq 100\}$ ,  $n \in N$ , and  $N$  is the number of CRNs. Similarly to spectrum measurements campaigns,  $Y_n$  must be repeated  $D$  times.

### 4.3 Admission Steps of CRNAC Decision Making

Although we are addressing the problem from network level perspective, we assume that the new CRN brings new customers. Therefore, admission for a new CRN should be based on the fact that there are enough spectrum bands to operate. Furthermore, the operation of a new CRN will impact on the existing CRNs through sharing the available spectrum. Therefore, when CRNAC admits any new network, it confirms to the administrators of the existing CRNs that there are enough available spectrum bands for the new CRN to operate. Furthermore, it assures the administrator of the admitted CRN that there are enough bands for its operation. *Since we aim to address the self-coexistence problems by resource management at **network level** rather than **user-level**, the metric used to measure networks performance is total utilised spectrum bands.* The suggested constraints of the CRNAC can be as follows:

- 1) Needed spectrum for the new CRN

- 2) Scalability of existing CRNs
- 3) Scalability of PNs
- 4) Safety spectrum guard

### 4.3.1 Needed Spectrum for the New CRN

There must be unoccupied spectrum bands for a new network, which must be similar to the utilisation of existing CRNs. Therefore, the question here is: which CRN from the existing networks should be used as a reference network in CRNAC's decision? If the decision is based on the utilisation amount of the poorest CRN performance (i.e. lower spectrum bands utilising), this means an overcrowded CRNs and saturated spectrum scenario is likely to occur. Therefore, we propose a hypothesis that there must be unoccupied spectrum bands equal to the average needed spectrum by the highest performance CRN (i.e. higher spectrum bands utilising). Thus, the first constraint states that there must be available bands equal to average required spectrum by highest performance CRN from its measurements  $\bar{Y}_n$  (where  $\bar{Y}_n = \sum_{t=1}^T y_n^t / T$ ). We refer to this as *Spec*, that can be calculated as:

$$Spec = \max \{ \bar{Y}_1, \bar{Y}_2, \dots, \bar{Y}_N \} \quad (4.1)$$

### 4.3.2 Scalability of Existing CRNs

The spectrum utilisation of all existing CRNs is strongly expected to increase. Therefore, the percentage increase in bands utilisation of each network must be considered in CRNAC. Thus we define  $\psi_n$  to be the expected scalability of a CRN ( $n$ ), where  $\{\psi_n \in \mathbb{R}^+ : 0 \leq \psi_n \leq 100\}$ .  $\psi_n$  can be easily anticipated (using a prediction method) from quantities of average utilisations  $\bar{Y}_n$  in all previous campaigns. Thus,  $\psi_{total}$  is the total expected scalability of all existing networks and is calculated as  $\psi_{total} = \sum_{n=1}^N \psi_n$ .

### 4.3.3 Scalability of PNs

Increasing spectrum utilisation from PNs on their licensed spectrum is another important factor that must be taken into consideration by CRNAC. Therefore, the regulator should predict the percentage increase of spectrum utilisation  $\Delta_{PN \text{ scalability}}$

by PNs' users  $\{\Delta_{PN\ scalability} \in \mathbb{R}^+: 0 \leq \Delta_{PN\ scalability} \leq 100\}$ . Similar to  $\psi_n$ ,  $\Delta_{PN\ scalability}$  can be predicted from previous measurements.

#### 4.3.4 Safety Spectrum Guard

It is well known that spectrum availability fluctuates most of the time. Furthermore, there is a heterogeneity of channels with different characteristics available over a wide frequency range. Thus, not all available channels can be exploited, for several reasons (e.g. low channel holding time, channel switching delay, etc.) [9]. There must be a consideration for a safety guard spectrum factor. It must be assigned carefully and needs continuous extensive calculation on spectrum bands characteristics. Thus we define it as  $\Delta_{guard}$ , where  $\{\Delta_{guard} \in \mathbb{R}^+: 0 \leq \Delta_{guard} \leq 100\}$ .

According to the aforementioned factors, the admission of a new CRN can be calculated as follows:

$$Diff = \bar{X} - Spec - \psi_{Total} - \Delta_{PN\ scalability} \geq \Delta_{guard} \quad (4.2)$$

$\bar{X}$  is the percentage average of spectrum availability measurements  $X$ . The meaning of Equation 4.2 is that if the  $Diff$  is larger than or equal to  $\Delta_{guard}$ , then a request for new CRN can be accepted. Thus the number of existing CRNs will be incremented by one. At the same time the CRNAC algorithm is capable of calculating the maximum number of CRNs allowed in the location. In this step there is no, need to consider  $\psi_{Total}$  and  $\Delta_{PN\ scalability}$ ; instead, only  $Spec$  and  $\Delta_{guard}$  are considered. Accordingly, admission of another new CRN can be based on the following constraint:

$$Diff_{new} = Diff - Spec \geq \Delta_{guard} \quad (4.3)$$

Consequently, as long as the constraint in Equation 4.3 is valid, it is possible to admit new CRNs. Thus, the maximum number of allowed CRNs will be obtained by repeating Equation 4.3.

Figure 4.1 shows the procedure of implementing CRNAC. Finally, the next section will examine the performance of the CRNAC algorithm.

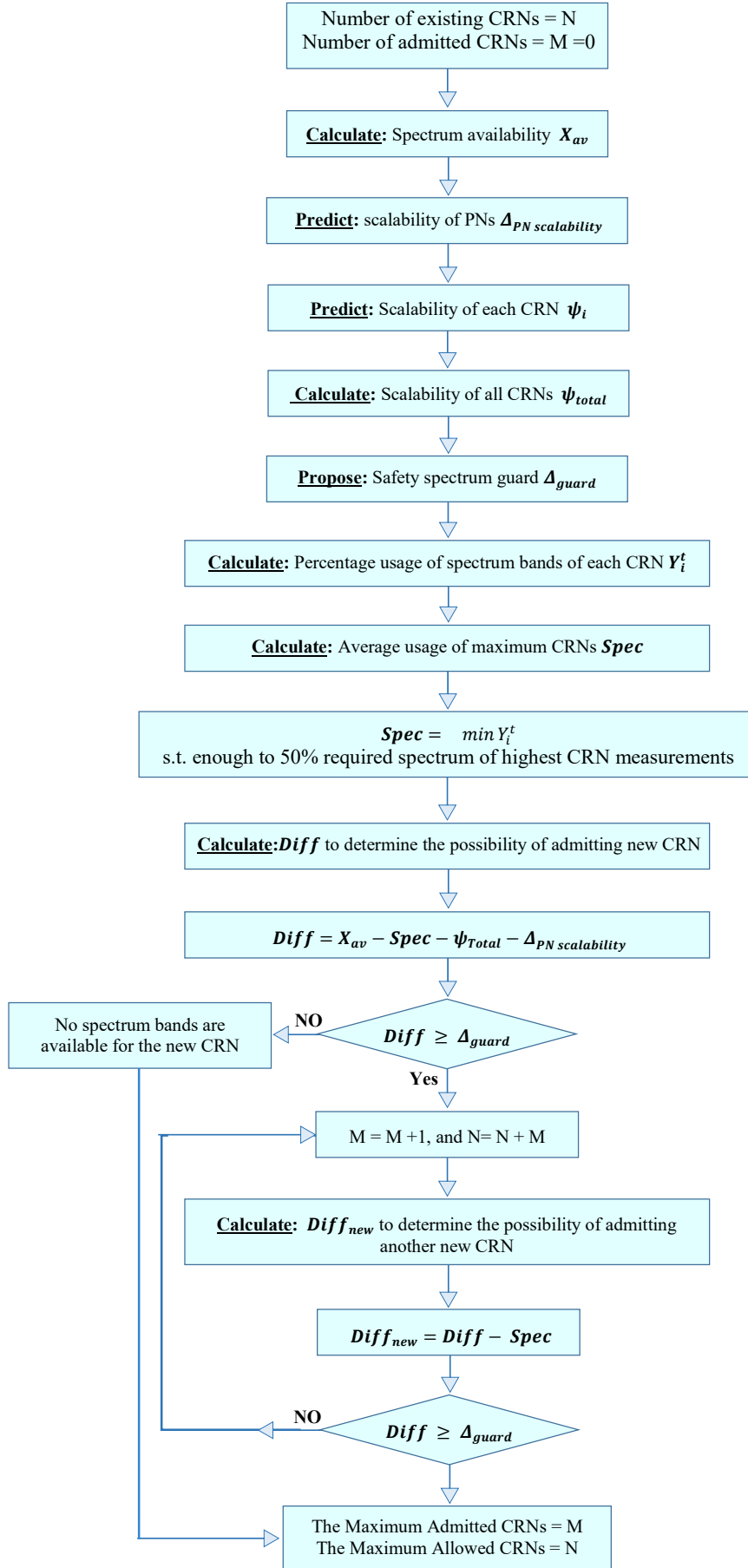


Figure 4.1: CRNAC algorithm flowchart.

## 4.4 Performance Evaluation

To examine the effectiveness of CRNAC, a numerical test was carried out using MATLAB (8.2.0.701). Before starting the evaluation, it was necessary to investigate spectrum measurement campaigns. We studied most of the campaigns that were surveyed recently in [27]. Clearly, the majority of the campaigns focused on the frequency range between 30MHz and 3GHz. The maximum measurement was found in the Barcelona campaign [192], where the occupancy was 22.57% in the frequency range 75 MHz to 3000 MHz. Accordingly, we consider this level of occupation in some of the experimental scenarios.

Turning now to the experimental assumptions, in order to achieve precise decisions by CRNAC, we assume that the regulators measure spectrum availability once in each hour, and repeat the measurements for 60 days (i.e.  $T = 24$ , and  $D = 60$  in CRNAC specifications). In addition, we assume that there are five CRNs that coexist in the available spectrum (i.e.  $N = 5$ ). As shown in Table 4.1, different percentages of the spectrum bands utilisation and expected scalability for the CRNs are assumed. Moreover,  $\Delta_{PN scalability}$ , and  $\Delta_{guard}$  are assumed to be 1% and 5 % respectively. Lastly, Table 4.2 summarizes the scenarios' assumptions as well as the remaining aforementioned factors.

Table 4.1: Factors assigned for existing CRNs and PNs.

Networks	Utilised Spectrum (%)	Expected Scalability (%)
CRN1	3 – 6	0.5
CRN2	6 – 9	1
CRN3	8 – 12	1.5
CRN4	5 – 8	0.6
CRN5	3 – 5	0.4
PNs	Variable to test	5



Table 4.2: Factors assigned for test specifications.

Factors	Assigned value	
Maximum spectrum occupancy before	Experiments of Section 4.4	Experiments of Section 4.6
	22.57% [192]	13% [27]
$\Delta_{guard}$	5%	
Number of location	1	
Number of campaigns	60	
Number of measurements	24	

### ***Scenario 1: $\Delta_{guard}$ Evaluation***

Based on Tables 4.1 and 4.2, in the first scenario, we examine the effect of the most important constraint of the CRNAC algorithm by varying the safety guard  $\Delta_{guard}$  of Equation 4-2 in three different percentage amounts: 5, 10, and 15. It is clear from Figure 4-2 that the admission started with less guard (e.g. 5%). Furthermore, the admission of smallest  $\Delta_{guard}$  (i.e. 5) increased up to two CRNs in comparison with the largest  $\Delta_{guard}$  (i.e. 15) at maximum spectrum availability. It is worth mentioning that in fact the maximum spectrum availability is not 55%, as illustrated in Figure 4.2. Instead, it is what remains from the utilisation of existing CRNs (i.e. five CRNs), PNs (i.e. 22.57% [2]), and safety guard. Furthermore, we suggest that the safety guard amount should be primarily dependent on the fluctuation of spectrum availability, which is the next scenario of evaluating CRNAC.

### ***Scenario 2: Variations in Spectrum Availability***

The second scenario was inspired by [193], where the spectrum occupancy measurements revealed that the spectrum utilisation varies between 4% and 15% of the total frequency range 700 MHz to 3 GHz. Therefore, the second scenario addresses the impact of the fluctuation of spectrum availability measurements on the CRNAC decision. In this scenario, three different fluctuations in spectrum availability are considered: firstly, less than 1% (i.e.  $\bar{X} \pm 0.499$ ) (referred to as **Less than 1 variation**); secondly, 5% variations (i.e.  $\bar{X} \pm 2.5$ ) (referred to as **Up to 5 variations**); and thirdly, 10% fluctuations (i.e.  $\bar{X} \pm 5$ ) (referred to as **Up to 10 variations**). As observed in

Figure 4.3, there are significant differences in admitting new CRNs at a higher variation (i.e. in **Up to 10 variations**) than the other cases. However, the differences in decision making between **Up to 5 variations** and **Less than 1 variation** increased above 30% of available spectrum (due to existing networks' activities).

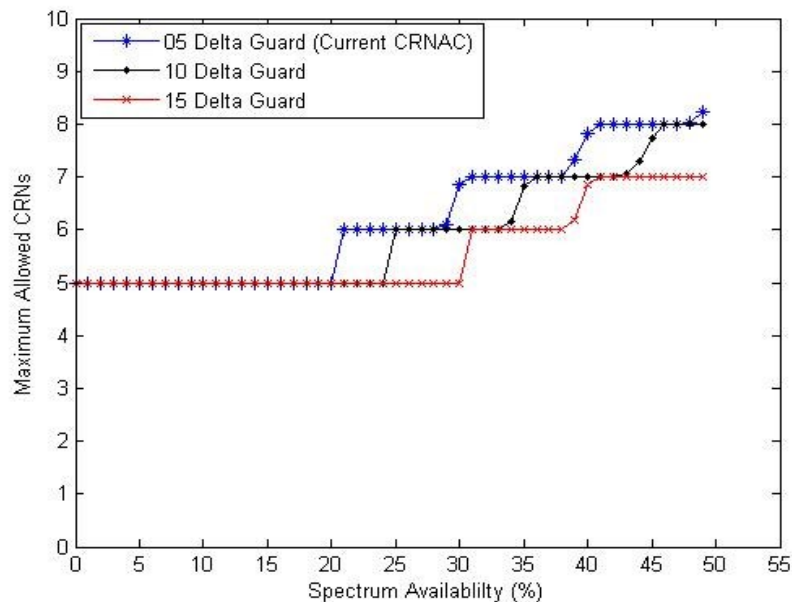


Figure 4.2: Scenario 1: Maximum number of allowed CRNs in different variations of spectrum occupancy measurements.

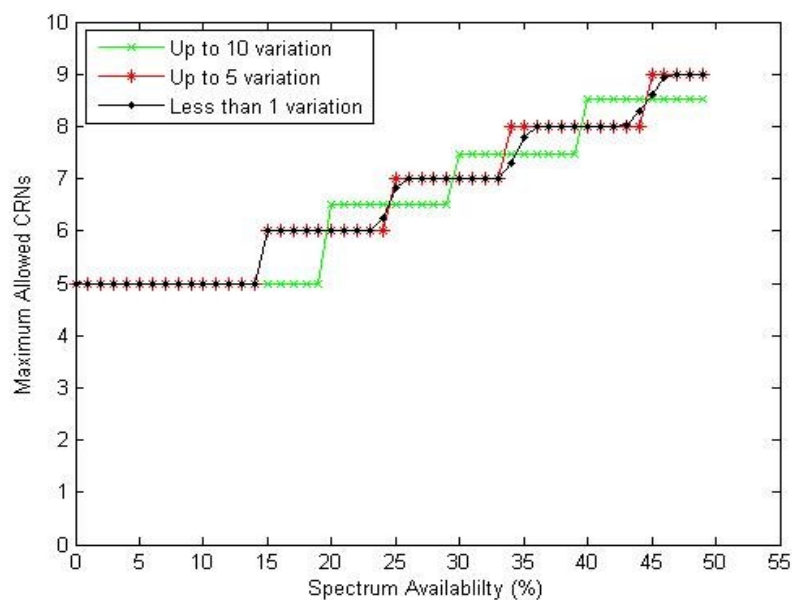


Figure 4.3: Scenario 2: Maximum number of allowed CRNs according to different  $\Delta_{guard}$ .

## 4.5 Impact of overcrowding in CRNs performance

So far, the number of utilised spectrum bands was the metric used to measure CRNs performance. In this section, we will evaluate via simulation the performance of CRNs under different channels availability. The aim of these tests is to show the degradations on CRNs QoS provision due to decreases in the available channels.

CRNs have been considered as heterogeneous networks capable of adapting themselves to different technologies (e.g. CDMA, 4G, WiFi, WiMAX, etc.). However, for simplicity, we simulate a CRN as a typical cellular network utilities LTE technology. We conducted our simulations using Vienna LTE-A Downlink System Level [194]. The simulator offers a high degree of flexibility and extensively uses the new object-oriented capabilities of MATLAB R2016b.

As summarised in Table 4.3, in the simulations, we considered our network to consist of a single site with a BS using an omnidirectional antenna allocated at the site centre with 25 m height. The coverage radius equals 500m, and Closed Loop Spatial Multiplexing (CLSM) LTE system. We evaluate network performance in five scenarios of channels availability: *14 channels*, *7 channels*, *3 channels*, *2 channels*, *1 channels*, referred to as *Ch14*, *Ch7*, *Ch3*, *Ch2*, and *Ch1* respectively. For simplicity, we assume the available channels have the same bandwidth value: 1.4 MHz. A variable number of SUs is assumed, which are uniformly distributed inside the cell.

Fig. 4.4 illustrates the average number of allocated Resource Blocks (RBs) of each SU in the five scenarios. Regardless of the number of existing SUs, decreases in the number of the utilising channels have led to decreased numbers of allocated RBs. As seen in the figure, increasing the number of SUs clearly led to decreases in their RBs. For example, in scenario *Ch14*, 30 RBs are allocated in the case of ten SUs; whereas this is significantly decreased to two RBs only in scenario *Ch1*. Accordingly, this decrease in the number of RBs will deteriorate SUs transmission rate.

Table 4.3: Simulation scenarios and parameter settings.

Model parameter	Value
Channel Type	Downlink
Tx Power	40 W
Tx antenna gain	15 dB
Rx antenna gain	0 dB
Rx beamwidth	Omni-directional
Number of channels	Variable (14, 7, 3, 2, 1)
Channels status	Idle (no PU activity)
Bandwidth	1.4 MHz
Antenna Type	CLSM 2x2 MIMO
Tx Antenna height	25 m
Rx antenna height	1.5 m
Polarisation	Vertical
Modulation	Adaptive (QPSK, 16QAM, 64QAM)
Scheduler	Round Robin
Number of USs	Variable to test (random, outdoor)
SUs mobility	3 km/h (Pedestrian)
Area of Study	1 km <sup>2</sup>
Noise Figure	8 dB
Noise Density	-174 dBm/Hz
Traffic model	Full buffer

Therefore, in Fig. 4.5, we evaluated the average achieved throughput by the SUs. One can observe how the transmission rates can be reduced by decreasing the number of the available idle channels. In other words, a significant improvement could be achieved by increasing the number of the available channels. In addition, as above, increasing the number of SUs decreases the achieved transmission rate. Therefore, to maintain the same transmission rate while increasing the number of SUs, there should be an increase in the number of exploited channels. For example, in scenario *Ch 3*, if the number of

SUs is increased from 10 to 40; then the network must increase its channels to 14 (i.e. scenario *Ch 14*) to keep providing the same transmission rates (i.e. 5 M b/sec).

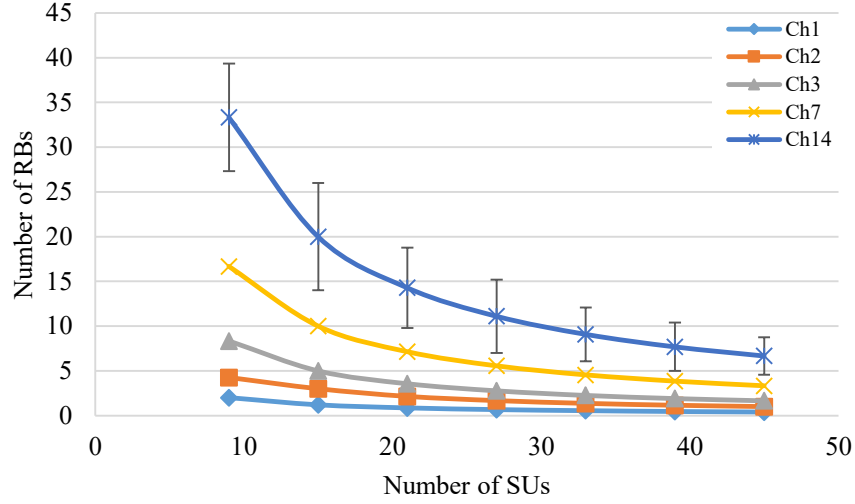


Figure 4.4: Average number of assigned RBs per SU.

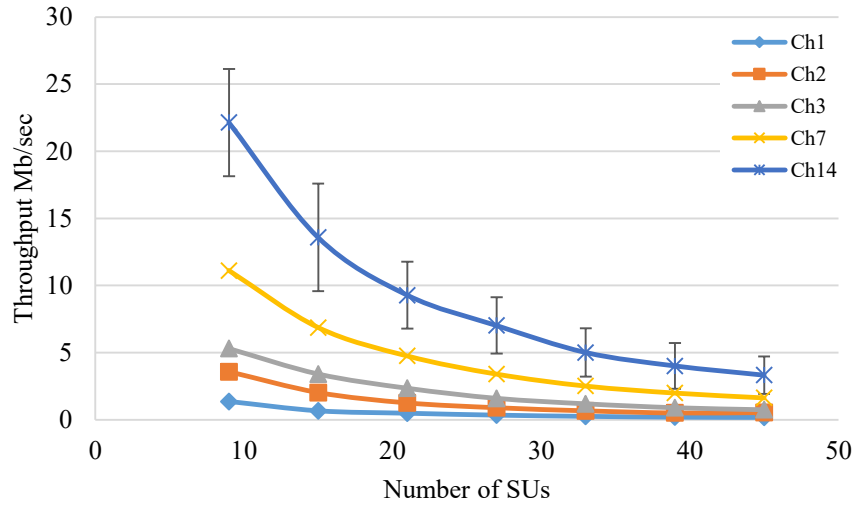


Figure 4.5: Average throughput per SU.

Lastly, decreasing the SUs throughput will impact negatively on network performance, and in consequence its trustworthiness and reliability. This is shown clearly in Figure 4.6, which compares the average overall CRN throughput in all cases. It is clear that increasing the available channels has led to a leap in the network throughput. Therefore, the key question is how CRNs can identify useful idle channels in an overcrowded situation. Finally, these simulations demonstrate that it is very important to assign a maximum number for admitting new CRNs to avoid a saturated spectrum situation.

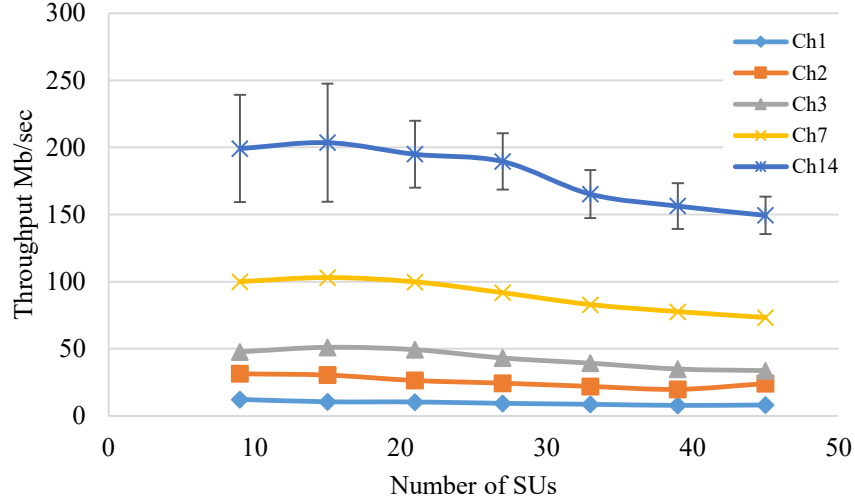


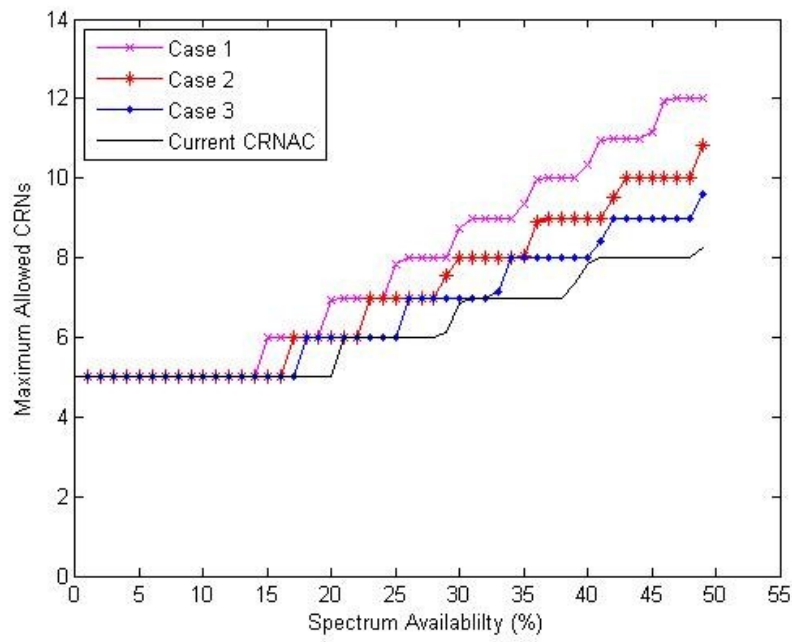
Figure 4.6: Overall network throughput.

## 4.6 Chapter Discussion: PUED vs. Existing Algorithms

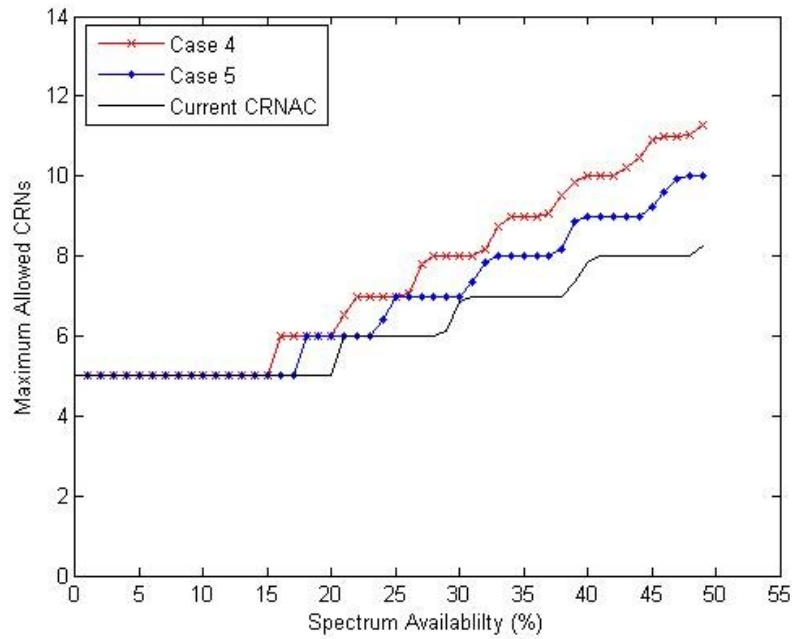
Since we do not have counterparts to prove the superiority of our algorithm, in the last scenario, we evaluated the *Spec* constraint in Equation 4.1. Thus we adopted five cases instead of choosing the average of highest performance CRN. These suggested cases are as follows:

- *Case 1*: Average of the minimum utilised spectrum by each CRN.
- *Case 2*: Average of the average utilisation of all CRNs.
- *Case 3*: Average of the maximum utilised spectrum by each CRN.
- *Case 4*: Average of the minimum usage of all CRNs together of each measurement in the campaigns.
- *Case 5*: Average of the maximum usage of all CRNs together of each measurement in the campaigns.

The first three cases are related to CRNs' utilisation, and the remaining cases are in terms of the usage in each test (i.e. measurements). Accordingly, we prefer to compare our algorithm with the first three cases in a particular figure, and the last two cases in another figure. As observed from Figure 4.7 (a, and b), admitting new CRNs in the aforementioned cases is better than our adopted case. A best explanation for these results is because of reducing the required spectrum for admitting networks. For instance, in Figure 4.7(a), case 1 is the less strict, while case 4 is the less strict one in Figure 4.7(b).



(a)



(b)

Figure 4.7: Scenario 3: part one: Maximum numbers of CRNs allowed in different cases.

In the second part of this section, we used Ruwi spectrum occupancy measurements in the Sultanate of Oman [27] to calculate the admission of the aforementioned cases as well as our adopted case. The calculations are listed in the second column of Table 4.4. It can be seen from the Table that our adopted constraint admitted seven new CRNs

only, while the cases admitted more networks. Additionally, case 1 is the least strict among the cases, and case 5 is the nearest to what we adopted in the current CRNAC. However, admitting a large number of CRNs may lead to a saturated spectrum situation, resulting in poor QoS in the new CRNs and degradation in QoS of existing networks. This argument will be debated in the last part of this scenario.

Although each CRN may have totally different spectrum requirements according to per-CRN secondary user population and spectrum usage policies, we assume that there must be enough spectrum bands for a new network to serve users similar to existing networks. To verify the reason of our adopted case of *Spec*, in the third part of the current scenario we compared the spectrum bands needed by existing CRNs with the admission constraint of each case. As observed from the third column of Table 4.4, all the cases failed in operating new admitted networks as CRN3, because their admission spectrum was low. The nearest case was when the CRNAC decision was based on case 3, where the reference spectrum was able to operate the new CRN as well as most existing networks.

Table 4.4: Expected performance of the admitted CRNs.

	<i>Part 2</i>	<i>Part 3</i>				
CRNAC decision	Maximum allowed CRNs according to [27]	Percentage of expected performance of admitted networks in compare with existing CRNs				
		<i>CRN1</i>	<i>CRN2</i>	<i>CRN3</i>	<i>CRN4</i>	<i>CRN5</i>
Case 1	10	70.6	0.0	0.0	3.7	100.0
Case 2	9.5	91.5	0.1	0.0	24.8	100.0
Case 3	9	100.0	16.5	0.0	50.2	100.0
Case 4	8.2	100.0	41.4	0.0	75.5	100.0
Case 5	8	100.0	65.6	0.0	97.2	100.0
Current CRNAC	7	100.0	100.0	50.0	100.0	100.0



## 4.7 Chapter Summary

In this chapter, in the second step towards realisation of CRNs spectrum sharing, the first network admission CRNAC algorithm has been proposed. CRNAC has demonstrated the effectiveness of the internetwork framework, CogMnet as proposed in Chapter Four. Several constraints that impact on CRNAC decisions have been modelled and analysed numerically. It has been argued that correct selection of CRNAC constraints in the CRNAC will ensure that there are sufficient spectrum bands available for the newly admitted CRNs in addition to the existing ones. Simulation experiments have been conducted to demonstrate the identified problem situation by assigning a maximum number of newly admitted CRNs in any of the CogMnet locations.

# Chapter Five: RCNC Network Core

*Progress lies not in enhancing what is, but  
in advancing toward what will be.*

*Khalil Gibran*

## 5.1 Introduction

CRNs are prone to emerging self-coexistence issues, such as *Spectrum Misdetection Probabilities*; *Inter-Cell Interference*; and *Primary User Emulation Attack*. While the existing solutions are able to some extent to mitigate these challenges, they are unable completely to prevent them. Furthermore, with the expected growth in the number of CRN types, inability to *model Secondary Users' Activities* is still an open issue. To tackle these four challenges, in this chapter, we propose a new design for an infrastructure-based CRN core, namely, Reliable Cognitive Network Core (RCNC). RCNC consists of two engines: Monitor and Coordinator Engine and Modified Cognitive Engine, where each engine comprises five components. RCNC utilises and integrates the information of spectrum sensing, geolocation databases, and CogMnet databases. We, therefore, proceed in this chapter to demonstrate the effectiveness of CogMnet in tackling self-coexistence issues. The content of this chapter will be appearing in IEEE Access Journal [195].

The remainder of this chapter is arranged as follows. Section 5.2 presents a detailed description of the architecture of RCNC including the assigned functionalities of its engines. In Section 5.3 we explain the time sequence processing of each component in RCNC. We present our evaluation of RCNC in Section 5.4 before we conclude the chapter in Section 5.5.

## 5.2 RCNC Architecture

The main goal of RCNC is to guarantee prevention of self-coexistence issues among overlapping and neighbouring CRNs, thereby improving CRNs' efficiency (i.e. service availability and reliability). As shown in Figure 5.1, RCNC is composed of two engines:

- 1) Monitor and Coordinator Engine (MNCE).
- 2) Modified Cognitive Engine (MCE).

### 5.2.1 System Model

Before delving into the functionalities of the engines, we call the system model of CogMnet the country is divided into locations, each consisting of a different number of overlapping and neighbouring infrastructure-based CRNs. We consider that RCNC is any network ( $n$ ) in location ( $l$ ), thus denoted as  $Net_{n,l}$ . Additionally, for simplicity, we assume that RCNC has only one cell coordinated by one base station defined as  $BS_{n,l}$ . RCNC depends upon three radio environment sources: 1) CogMnet databases; 2) spectrum sensing component; and 3) geolocation databases. Therefore, according to CogMnet, the location ( $l$ ) is coordinated via database ( $DB_l$ ) that contains the three storages ( $NL_{DB_l}$ ,  $RT_{DB_l}$ , and  $HS_{DB_l}$ ).

### 5.2.2 MNCE Functionalities

The target of MNCE is to prevent ICI, spectrum misdetection, and detect PUEA details that may contribute to deterring it. We now describe the functionalities of each component in MNCE.

#### 5.2.2.1 Cells Monitoring Manager

- 1) Monitors  $NL_{DB_l}$  in CogMnet (the first environment resource scheme of RCNC) to create the following two lists: firstly, the *Overlap list* to record the information about the overlapping networks' cells. Secondly, *Neighbouring list* contains details of cells in

$BS_{n,l}$  vicinity. The stored information in both lists includes the BSs sequence number (as given in CogMnet).

2) Sends the *Overlap list* to the *SUs Activity Modeller Component* in MCE. Similarly, forwards to it the following components in MNCE: *PUEA Identifier* and *Sensing Supporter*.

3) Reports *Neighbouring list* to the components: *Inter-Cell Interference Coordinator* and *Network Extending Planner* in MCE, respectively.

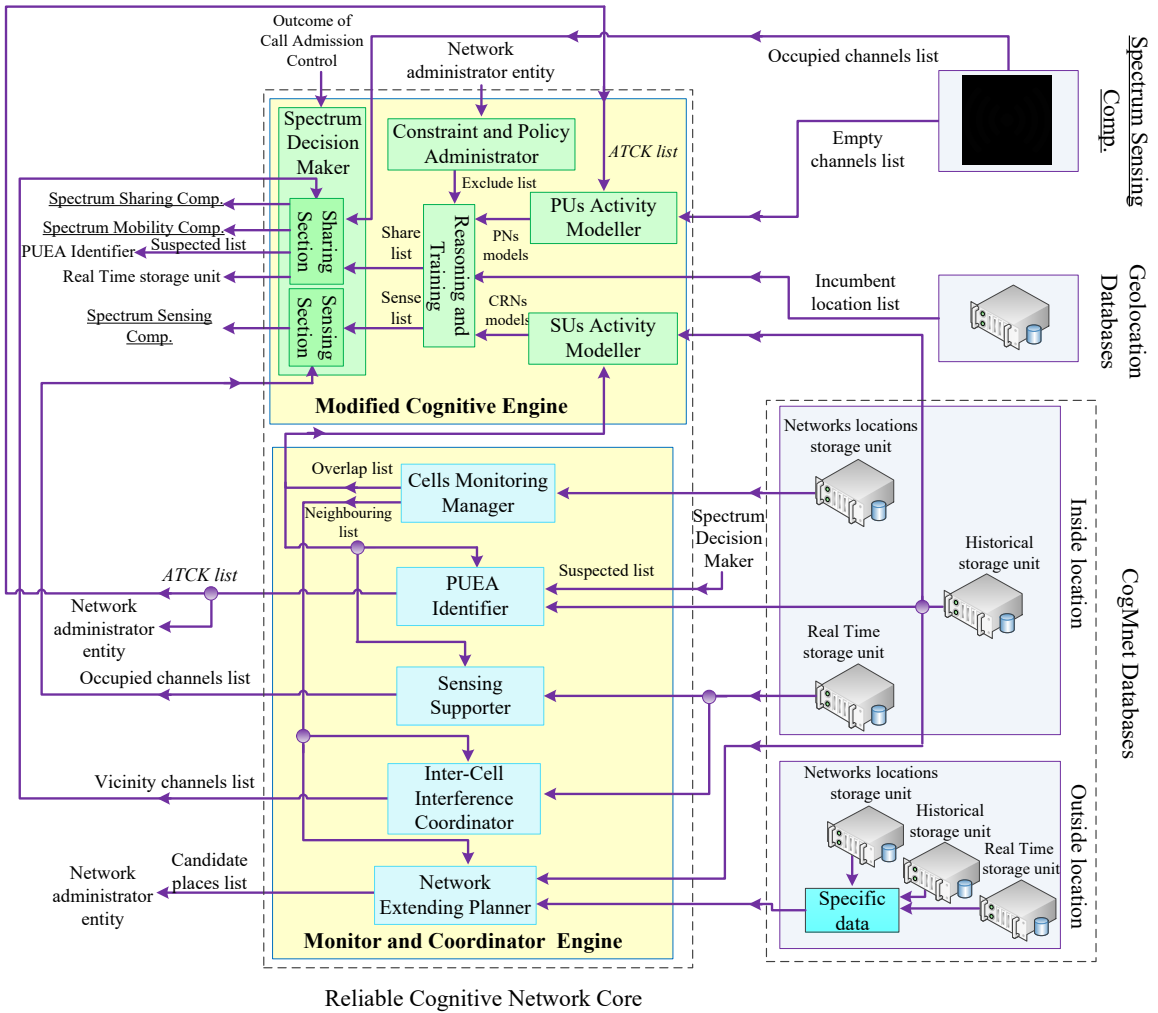


Figure 5.1: Architecture of RCNC.

4) Both files must be continuously updated for any changes (e.g. establishing new cells or terminating existing ones).

5) The **contribution** of this component is to reduce the search complexity in the parts that they may send.

### 5.2.2.2 PUEA Identifier

1) Since all network utilisations are recorded, it is easy to determine the attacks in terms of attackers, frequencies, time and period. After every handing off,  $BS_{n,l}$  may need to verify for some evacuated channels whether this was caused by the real PU or PUEA. As a consequence, this will prevent devising unreliable models for the attacked channels. Therefore, we believe that this component will contribute to preventing PUEA issues. For this reason we named this algorithm PUEA Deterrent (PUED). The procedure of implementing PUED will be described in Chapter Six.

2) PUED will list the specifications of the offender base station sequence and attack frequency and time in *ATCK list* (referring to ‘Attack’).

3) The **contributions** of this component are to: a) Inform the network administrator entity of *ATCK list* for using it as evidence against the aggressive CRN(s). ; and b) Forward the *ATCK list* to *PU Activity Modeller Component* in MCE to avoid considering PUEAs as normal PU activities.

### 5.2.2.3 Sensing Supporter

1) Before starting every sensing task, this component will observe  $RT_{DB_l}$  to identify the under-utilised channels by other overlapping CRNs and store their details in *Overlapping channels list*.

2) Reports the list to the *Sensing Section* in *Spectrum Decision Maker Component* to remove the listed channels from sensing duty.

3) The **contributions** of this component are to: a) Prevent collision among CRNs caused by misdetection probabilities; and b) Improve spectrum sensing efficiency. Very briefly, the second contribution can be explained as follows: if the CRN uses the filter-bank wideband detection [183], removing some channels (found as occupied in  $RT_{DB_l}$ ) will lead to reducing the number of operated filters, thus reducing power consumption.

#### 5.2.2.4 Inter-Cell Interference Coordinator

- 1) Before starting the  $BS_{n,l}$  to utilise the candidate channels (100% not occupied), this component will monitor  $RT_{DB_l}$  and obtain the specifications of the channels of neighbouring cells, then store them in a list denoted as *vicinity channels list*.
- 2) Sends the file to *Sharing Section* in the *Spectrum Decision Maker Component* to avoid selecting the recorded channels for communication.
- 3) Therefore the **contribution** of this component will be to prevent co-channel interference problems.

#### 5.2.2.5 Network Extending Planner

- 1) Analyses  $HS_{DB_l}$  to determine the channels utilised by other cells outside the network's location.
- 2) Compares these utilisations with the spectrum availability in their area to create a *Candidate places list* of the best areas that the CRN may extend to.
- 3) Forwards the list to the network administrator entity. **Note** that the number and the duration of preparing files are beyond the scope of this research.
- 4) Thus the **contribution** here is planning for future expansion, which is necessary to extend CRN coverages, leading to new revenue sources.

### 5.2.3 MCE Functionalities

The functionalities of MCE can be summarised as follows:

#### 5.2.3.1 SUs Activity Modeller

- 1) Analyses the utilised channels of the overlapping cells in  $HS_{DB_l}$  in order to model their activity (let us define it as *CRNs Models*).
- 2) Reports the developed models to the *Reasoning and Training Component*.
- 3) The **contribution** here is the ability of the network to model SUs activity. This modelling is necessary for CRNs to achieve a fair competition for the available channels, particularly the recently admitted CRNs, which are not able to distinguish whether the spectrum is occupied by PUs or SUs.

### 5.2.3.2 PUs Activity Modeller

1) Excludes the channel listed in *ATCK list* (sent from *PUEA Identifier Component*) from the detected channels by the Spectrum Sensing Component (the second environment resource scheme of RCNC). It is important to mention that the channels detected by the Spectrum Sensing Component are those utilised by PUs only, because the *Sensing Supporter Component* (in MNCE) has removed the channels occupied by other CRNs from the sensing task.

2) Analyses the left channels in order to model PUs activity.

3) Forwards the obtained models to the *Reasoning and Training Component*.

4) Accordingly, the **contribution** of this component is preventing the network from devising unreliable models for PUs behaviours by avoiding considering PUEAs as PUs activities.

### 5.2.3.3 Constraint and Policy Administrator

1) This component is responsible for creating a list called '*Exclude list*' that consists of unauthorised channels. These channels include military channels or any band the regulator may prevent in the future, information which must be provided by the network administrator entity.

2) Reports the *Reasoning and Training Component* to remove the listed channels from utilisation.

3) Thus, the **contribution** of this component is ensuring that the CRNs follow the regulators' policies.

### 5.2.3.4 Reasoning and Training

1) This intelligent component receives both PUs and SUs activities models and idle channels from geolocation databases (the third environment resource scheme of RCNC). It then uses its experience to learn its capabilities from the surrounding environment. Lastly, it predicts two types of lists: *share list* and *sense list*. While *share list* may include the best channels to utilise, *sense list* consists of the channels that need to be sensed.

2) Sends the *share list* to *Sharing Sections* in *Spectrum Decision Maker Component*.

3) Similarly, reports the *sense list* to *Sensing Section* in *Spectrum Decision Maker Component*.

4) The **contribution** of this component is to prepare the best candidate channels to sense and share.

### 5.2.3.5 Spectrum Decision Maker

1) This element is the most important part in drawing network performance. It consists of two sections: *Sensing Section*, and *Sharing Section*. The *Sharing Section* receives both the *share list* and *vicinity channels list*. It then removes the recorded channels of the *vicinity channels list* from the *share list* and selects the required number of channels to share (assigned by network call admission control). Lastly, it sends them to: a) the Spectrum Mobility Component to adapting the network to the selected channels and then to start utilising them; b) the Spectrum Sharing Component to carry on of exploiting the under-utilising channels; and c) the CogMnet to be written in  $RT_{DBI}$  as channels are in use by  $BS_{n,l}$ . **Note** that both Spectrum Mobility Component and Spectrum Sharing Component are beyond our scope in this research.

2) The *Sensing Section* receives two lists at different times: **Firstly**, the outcome of Spectrum Sensing Component in case of reactive handing off on under-utilising channel(s). The section then chooses a certain number of channels that need to be verified from PUEA and sends this information to *PUEA Identifier Component*. **Secondly**, it receives a list of the candidate channels from the *Reasoning and Training Component* and then removes the occupied channels list by overlapping cells (sent by the *Sensing Supporter*). The remaining channels will be forwarded to Spectrum Sensing Component for detecting their status. Note that the Spectrum Sensing Component is outside the research scope (which must be performed cooperatively by the base stations and (selected or all) SUs).

3) Therefore, the **contributions** of this component are: **Firstly**, selecting the required best channels to share at which both ICI and misdetection will be eliminated. **Secondly**, identifying the final list of channels to be sensed. **Thirdly**, reporting to the network administrator entity the selected channels to share in order to report them to CogMnet. **Lastly**, sending a list of suspected channels to *PUEA Identifier Component*.

Accordingly, the contributions of each component in RCNC can be summarised as in Figure 5.2. Finally, in this section, we described RCNC engines including the components of each engine. In the next section, we will show the procedure of implementing the functionalities of each component.



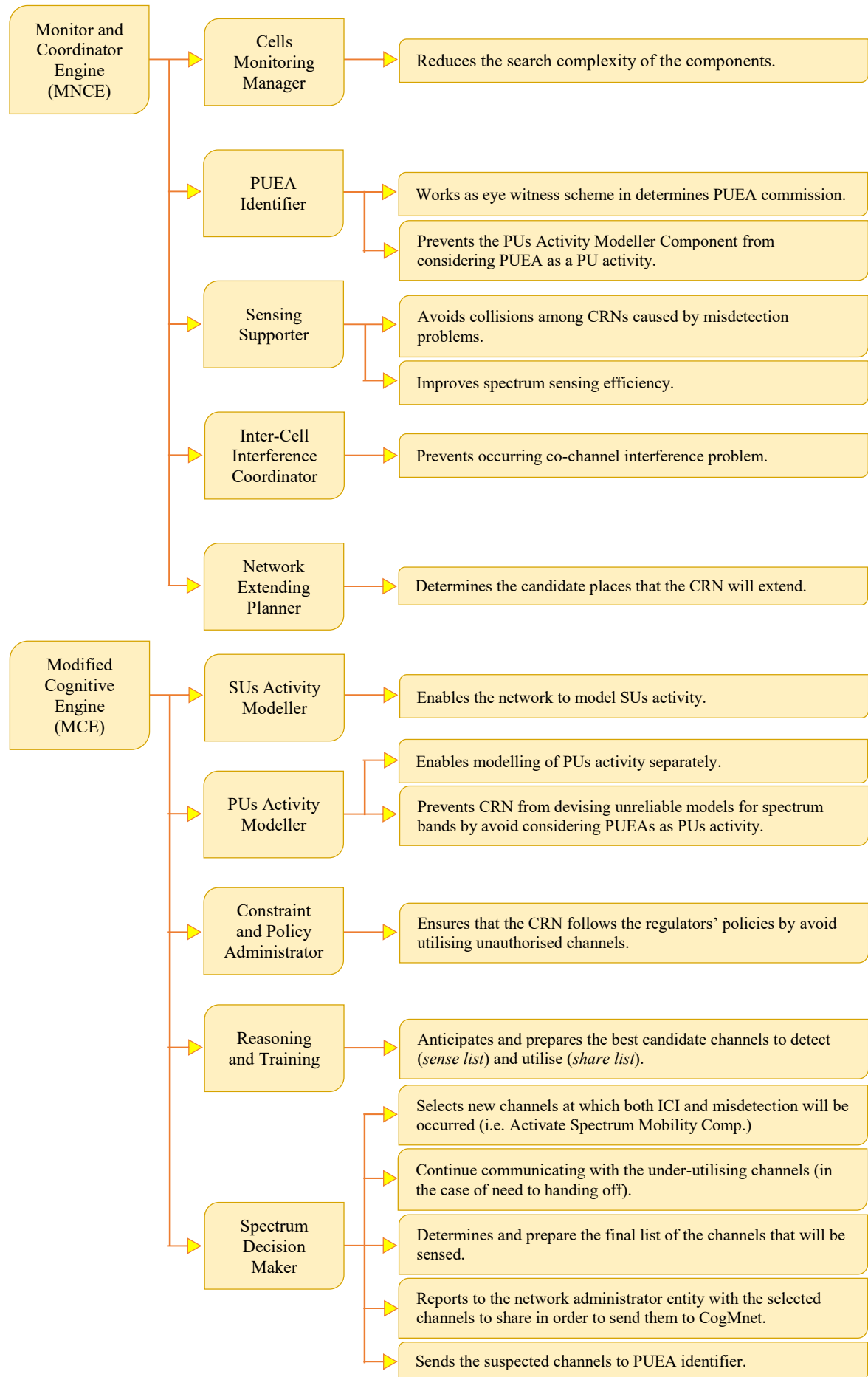


Figure 5.2: Summary of the contributions of RCNC.

## 5.3 RCNC in Action

For further clarification on RCNC engines, we explain here the time sequence processing the role of each component. We divide the processing into five time sequences. Note the period of each time could be different and depends on the network processing speed capabilities. As depicted in Figure 5.3, the sequences are as follows:

### 5.3.1 Sequence One

Here, the *Cells Monitoring Manager Component* starts by (in the first-time operation) creating/updating (in the later processes) the two lists: overlap list and neighbouring list from  $NL_{DB_l}$  in CogMnet database.

### 5.3.2 Sequence Two

In the case of PUEA suspiciousness, *PUEA Identifier* implements the PUE algorithm to identify attackers' specifications (i.e. attackers' cells, frequencies, time and period) and record them in the *ATAC list*. This report will be sent to both the network administrator entity and *PUs Activity Modeller Component* in MCE.

### 5.3.3 Sequence Three

In this level, three components will be implemented. Firstly, *Constraint and Policy Administrator Component* provides details of unauthorised channels and updates the list with the newly prohibited frequencies. Secondly, *SUs Activity modeller Component* utilises  $HS_{DB_l}$  in CogMnet of the overlapping cells, leading to enabling CRNs to determine the activities of other CRNs (i.e. SUs activity). Lastly, *PUs Activity modeller Component* models the outcome of Spectrum Sensing Component because *Sensing Supporter Component* has removed the occupied channels by other CRNs. Note that PUEA Identifier will inform *PUs Activity modeller component* of the channels that have been under PUEA.

### 5.3.4 Sequence Four

*Sensing Supporter Component* examines  $RT_{DB_l}$  the occupied channels of the overlapping cells and sends the information to Spectrum Decision Maker to remove these channels from the sensing task.

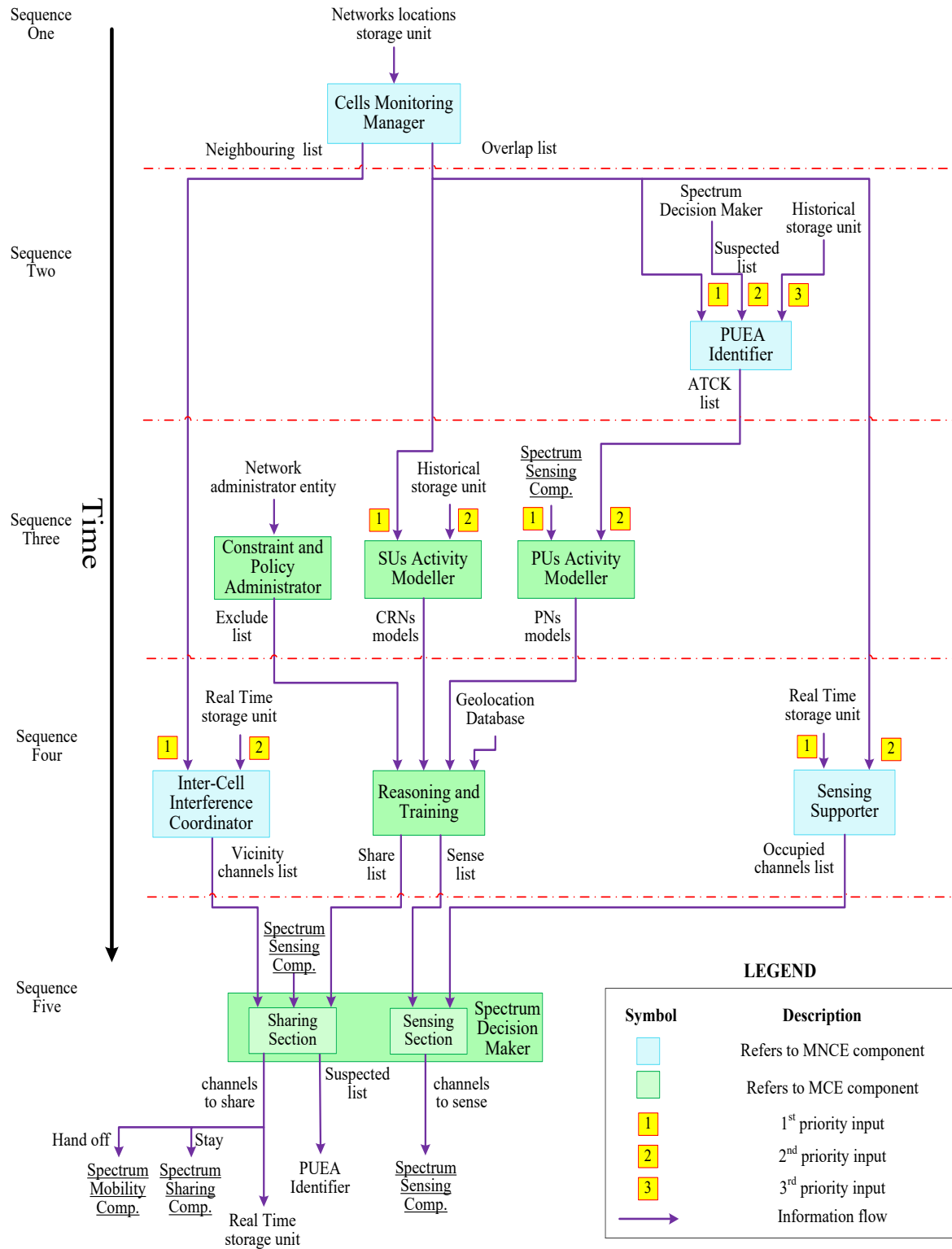


Figure 5.3: Time sequence processing of RCNC's components.

### 5.3.5 Sequence Five

*Inter-Cell Interference Coordinator Component* exploits  $RT_{DBI}$  storage in CogMnet to make a list of the neighbouring cells channels and sends it to *Spectrum Decision Maker Component* to avoid selecting any idle channels similar to the listed ones.

One can observe from Figure 5.3 that *Network Extending Planner* is not considered in the processing sequence, since the period required for preparing reports depends on network strategy (i.e. network administrator entity). Furthermore, this time may differ from one system to another; therefore, it is outside this research scope.

## 5.4 RCNC Evaluation

In this section, we evaluate RCNC performance using ICS Designer by ATDI [196]. Although CRNs are heterogeneous networks, we adopted LTE technology as a communication technology for our networks. To obtain realistic results, we conducted extensive simulations in Brussels, Belgium, because we particularly preferred to choose an urban environment.

As depicted in Figure 5.4, we simulated three overlapping CRNs utilising CogMnet in their coexistence, where each network has twenty SUs. We assumed that each network consisted of a single site with a BS using an omnidirectional antenna located at the site centre with 25 m height. We located the BS of the 2<sup>nd</sup> network 50 meters away from the BS of the 1<sup>st</sup> network. Additionally, but in the opposite direction, we established the BS of the 3<sup>rd</sup> network 350 meters away from the BS of the 1<sup>st</sup> network. Table 5.1 presents the key parameters used in our simulations.

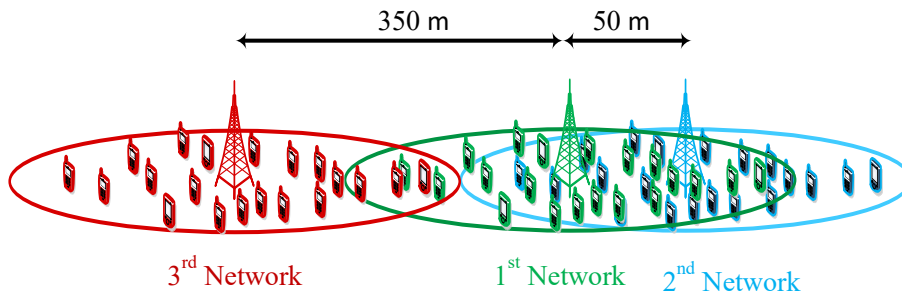


Figure 5.4: Configuration of the simulations.

To improve the superiority of RCNC over conventional CRNs, we have chosen to evaluate the performance in terms of SUs' achieved throughput, received SINR and Reference Signal Received Quality (RSRQ). The evaluation is carried out in three scenarios. As summarised in Table 5-2, the scenarios are as follows:

- 1) *Scenario RCNC*: all networks' cores are as RCNC.
- 2) *Scenario CRN50*: the second network is a conventional CRN.
- 3) *Scenario CRN350*: Here, we simulate the third network as a conventional CRN.

Table 5.1: Simulation parameter settings.

Model parameter	Value
No. of channels	3 channels
Bandwidth	6 MHz
Tx Power	40 W
Tx antenna gain	15 dB
Rx antenna gain	0 dB
Antenna Type	CLSM 2x2 MIMO
Tx Antenna height	40 m
Rx antenna height	1.5 m
Modulation	Adaptive (QPSK, 16QAM, 64QAM)
Scheduler	Round Robin
No. of SUs	20 (random, outdoor)
SUs mobility	3 km/h (Pedestrian)
Noise figure	8 dB
Traffic model	Full buffer
Simulation time	10 simulation runs with 10 seconds each

Table 5.2: Simulation scenarios.

Scenario	1 <sup>st</sup> Network	2 <sup>nd</sup> Network	3 <sup>rd</sup> Network
RCNC	RCNC	RCNC	RCNC
CRN50	RCNC	Conventional CRN	RCNC
CRN350	RCNC	RCNC	Conventional CRN

Figure 5.5 compares the achieved throughput in each SU in the 1<sup>st</sup> network in the three scenarios. Obviously, by implementing RCNC networks, a significant improvement can be obtained in *RCNC Scenario* compared to the other two scenarios. Additionally, the best explanation of the difference in achieved throughput between the first ten SUs and the second ten users is that they are farther from the BS and are therefore affected by attenuation loss barriers such as tunnels and buildings. Figure 5.6 presents the received SINR at each SU in the three scenarios. The great improvement experienced by each user is clear in *Scenario RCNC*. The low throughput achievement in the first ten SUs is caused because of their low received SINR.

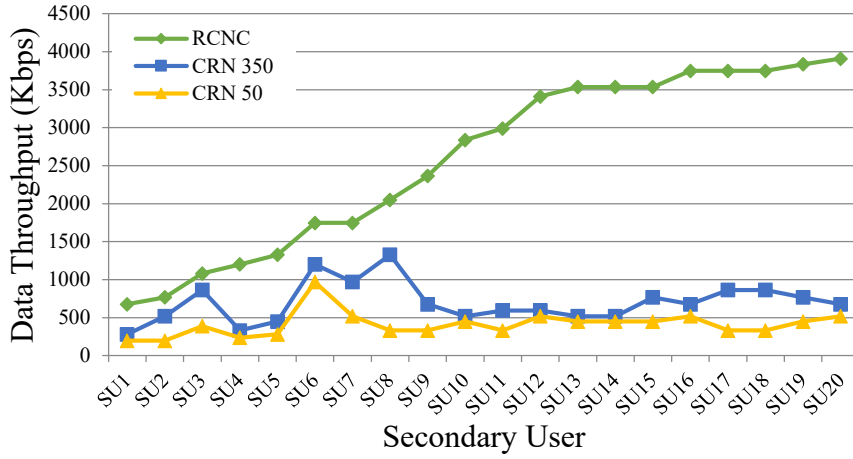


Figure 5.5: Throughput per each SU in the scenarios.

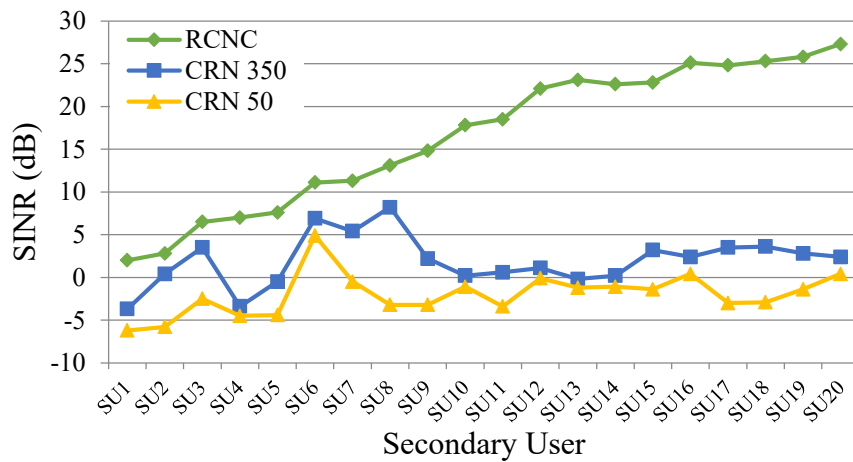


Figure 5.6: SUs' SINR gain in the scenarios.

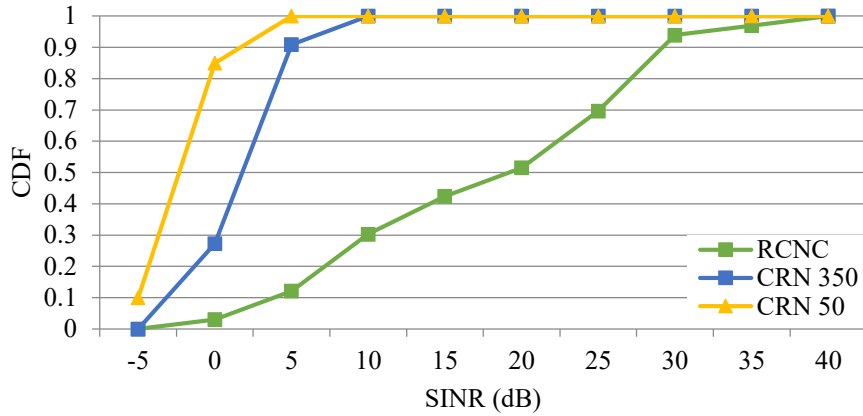


Figure 5.7: The CDF of SUs' SINR.

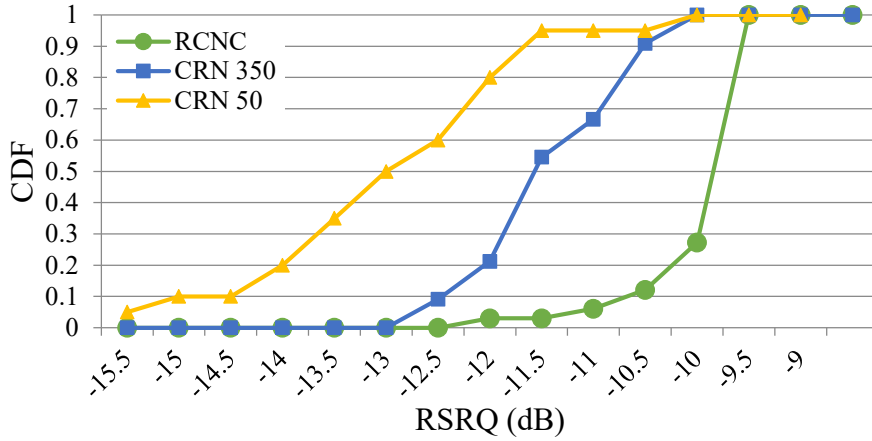


Figure 5.8: The CDF of SUs' RSRQ.

Figure 5.7 illustrates the Cumulative Distributed Function (CDF) of the received SINR in each SU. From the figure, one can see that in *Scenario RCNC*, the SUs received  $\leq 40$  dB, whereas the users of *Scenario CRN50* and *Scenario CRN350* received  $\leq 5$  dB and  $\leq 7.5$  dB respectively. The main reason for this is the impact of misdetections and ICI interference that come from conventional CRN in *Scenario CRN50*, and *Scenario CRN350* respectively. Figure 5.8 shows the CDF of Reference Signal Received Quality (RSRQ) which determines end-users' connectivity. Among the scenarios, *Scenario RCNC* offers a large performance enhancement. It is clearly seen in Figure 5.8 that the CDF of RSRQ in *Scenario RCNC* is better than the other scenarios. For example, when RSRQ is -11 dB, *Scenario RCNC* reaches 8%, but in *Scenario CRN50*, and *Scenario CRN350* their CDF is near to 68%, and 93% respectively.

## 5.5 Chapter Discussion

The existing solutions to mitigate the challenges: *Spectrum misdetection*, *Inter-cell Interference*, *Inability to model SUs activity*, and *Primary User Emulation Attack* are unable completely to tackle them. **Firstly**, regarding *spectrum misdetection*, sensing capabilities are not perfect and hence the possibility of interference always exists. **Secondly**, for *Inter-cell Interference* avoidance, several ideas have been proposed in the literature, all with the primary assumption that all CRNs are willing to exchange their resource information. However, none of them clarified how can this be achieved. **Thirdly**, enabling the *modelling of SUs activity*: This is very important for CRNs to be able to compete for spectrum opportunities among themselves. However, CRNs are so far still incapable of modelling SUs activity because they are unable to differentiate between the behaviour of all PUs and coexisting CRNs activities. The impact of this deficiency can be seen in real time when the networks devise unreliable models for the spectrum. **Lastly**, *Primary User Emulation Attack*: While the existing schemes are promising on detecting PUEA, they are not able to prevent CRNs from performing attacks.

From the conducted simulation results, we see that RCNC is able to overcome self-coexistence problems and prevent the networks performance deterioration. Therefore it is important to consider incorporating RCNC in the design of all infrastructure-based CRN types (Conventional CRNs, WRAN, and White-Fi networks).

## 5.6 Chapter Summary

In this chapter, we proposed a framework of a new infrastructure-based CRN, RCNC, for an efficient solution to prevent four different critical CRNs' self-coexistence issues: Spectrum misdetection; ICI; PUEA; modelling of SUs activity. In addition to all of the above, RCNC is expected to improve networks' spectrum sensing efficiency and plans to extend network coverage. To perform these tasks, RCNC utilises and integrates the information of spectrum sensing, geolocation databases, and CogMnet databases. From the above results, we see that RCNC is able to overcome self-coexistence problems and prevents the networks performance deterioration.

In the next chapter, we will describe the PUED algorithm and argue how the attack can be deterred.



# Chapter Six: PUED Algorithm

*A little knowledge that acts is worth infinitely  
more than much knowledge that is idle.*

*Khalil Gibran*

## 6.1 Introduction

CRNs are prone to emerging coexistence security threats such as PUEA. Specifically, a malicious CRN may mimic PUs signal characteristics to force another CRN to vacate its channels thinking that PUs have returned. While existing schemes are promising to some extent on detecting PUEAs, they are not able to prevent the attacks. In this chapter, we propose a PUEA Deterrent (PUED) algorithm that can provide PUEAs' commission details: *offender CRNs* and *attacks' time and bandwidth*. PUED is implemented by PUEA Identifier Component in MNCE in RCNC prior to every handing off. According to RCNC design, the determined *ATCK list* (attack) by PUED will be sent to a) the network administrator entity for using it as evidence against the aggressive CRN(s); and b) to *PUs Activity Modeller Component* in MCE in RCNC to avoid considering PUEAs as normal PU activities, which means preventing devising unreliable models for the attacked channels. The content of this chapter will be appearing in IET Networks Journal [197].

The remainder of this chapter is organised as follows: Section 6.2 discusses our vision for the required steps to deter PUEA. Section 6.3 explains the mechanism of the PUED algorithm using a numerical example. Section 6.4 briefly highlights crime prevention methods and shows the similarities between our algorithm and CCTV systems. Section 6.5 evaluates CRN performance under expected contribution of PUED. Finally, in Section 6.6 we summarise the contribution of this chapter.

## 6.2 Preliminaries to PUED: Need for a Deterrence Method

While the existing schemes are promising on detecting PUEA (listed in Chapter Two), they are not able to prevent CRNs from performing attacks. Furthermore, the offender network could pretend that the interference was committed unintentionally (i.e. misdetection of the occupier). Therefore, to implement a successful PUEA deterrence policy, we need to guarantee the following steps:

- *Step 1*: Prevent spectrum misdetection issue among CRNs.
- *Step 2*: Implement an evidence-based algorithm that shows the commission of the PUEA.
- *Step 3*: A self-coexistence system that punishes any CRN that may violate the coexistence rules.

To achieve the **first step**, we proposed RCNC in the previous chapter to utilise the real-time databases of CogMnet. Thus, before starting to utilise any channel, *Sensing supporter Component* in RCNC allows CRNs to check their local database (in CogMnet) to verify whether another overlapping CRN is using the channel. Regarding the **second step** according to the criminology literature, identifying caller ID and Closed-Circuit Television (CCTV) systems have had significant impacts in deterring nuisance calls and criminal activity respectively [198] [199]. This point has motivated us to propose an algorithm capable of determining PUEA commission details. For the **last step**, severe financial penalties played a significant role in decreasing reoffending rates [200]. As such, the regulator must release a self-coexistence system that punishes offenders for violating the rules.

Therefore, as we will see in Section 6.5, there is a need for a PUEA detector that serves as an eye witness scheme like CCTV systems. In this section, we describe how PUED can provide attack details.

### 6.3 Problem Formulation

We adopt the system model of CogMnet where a different number of infrastructure-based CRNs coexist in  $L$  locations. Let us suppose a base station  $BS_{n,l}^x$  attempts to apply the algorithm.

Basically,  $BS_{n,l}^x$  is able to utilise a different number of channels for different numbers of users. For generality, let  $U$  be the number of utilised channels. Due to exploiting unlicensed channels,  $BS_{n,l}^x$  must evacuate its channels once other activities are detected. Thus, we define  $V$  as the number of the evacuated channels where  $V \subseteq U$ . Actually, not all of  $V$  channels could be forced to release because of PUEA arrivals. Therefore, let  $S$  be the number of the channels that need to be verified where  $S \subseteq V$ . Additionally, let  $fmax_s$  and  $fmin_s$  be the frequencies of the  $ch_s$  where  $s \in S$ . These channels have different utilisation starting times and dates which can be defined as  $utti_s$  and  $utda_s$  respectively. However, they have the same evacuation time and date, which we represent as  $evti$  and  $evda$ .

### 6.4 Mechanism of PUEA Algorithm

The PUED algorithm aims to show the commission of PUEA by offender networks. The algorithm is capable of providing complete information on PUEA commission. To do this, the algorithm exploits the information of overlapping CRNs' utilisation in CogMnet databases. The mechanism of PUED is shown in Fig. 3, where the algorithm will create a number of lists as follows:

- 1) *Overlap list*: This list is created by *Cells Monitoring Manager Component* in MNCE. As explained in Chapter Five, the component monitors  $NL_{DB}$  in order to prepare a list consisting of information on overlapping cells (of other CRNs) with  $BS_n$  coverage area. Here, we denoted this list as  $B$ , where the identity of each cell will be referred to by its BS sequence.

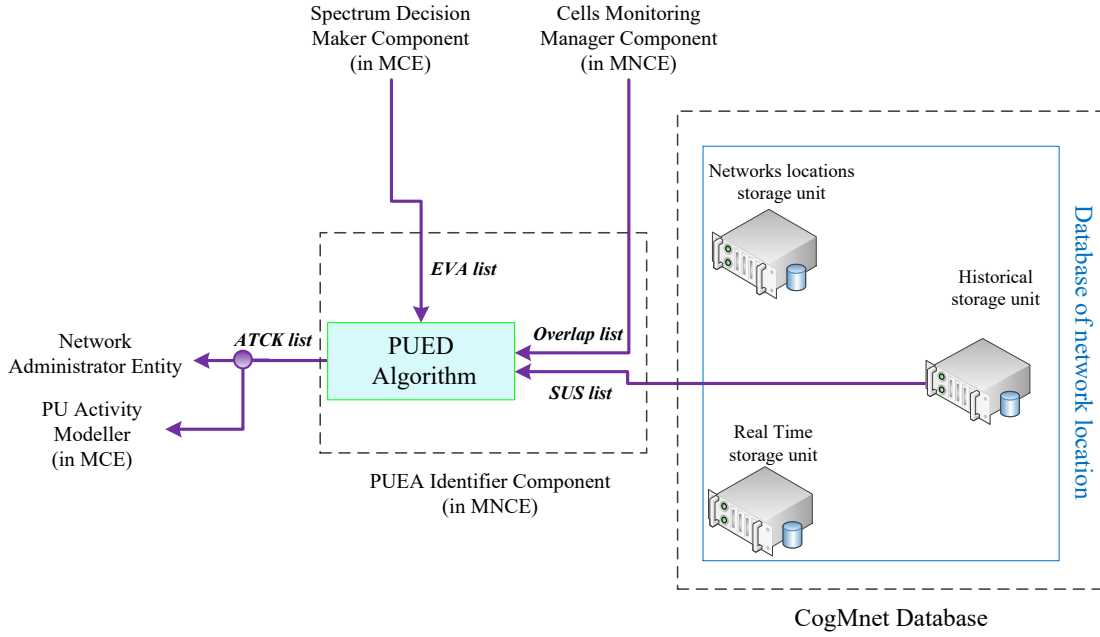


Figure 6.1: Mechanism of implementing PUED.

2) *EVA list*: This list is dedicated to storing the details of the evacuated channels that need to be checked from PUEA (i.e.  $S$ ). The information will be received from the Spectrum Decision Making component in the network's Cognitive Engine. The required details include the following:

- a) Frequencies:  $fmax_s$  and  $fmin_s$  of each  $ch_s$  ( $s \in S$ ).
- b) Periods: The times and dates of both utilisation ( $utti_s$  and  $utda_s$ ) and evacuation ( $evti$  and  $evda$ ) for the  $S$  channels.

3) *SUS list*: In this stage, PUED will start monitoring  $HS_{DB}$  to determine the suspected channels that are utilised by the overlapping CRNs. According to CogMnet, if any CRN utilises any channel the network should send its under-utilized channels to  $DB$ . Thus, our algorithm proceeds to search the channels that are utilised by overlapping cells within the exploiting period of evacuated channels (i.e. between ( $utti_s$  and  $utda_s$ ) and ( $evti$  and  $evda$ )). Let us denote the obtained channels as  $E$  and their information will be stored in a file known as *SUS list* (referring to ‘suspected’). The recorded details are as follows:-

- a) Base station sequence: Sequence base station number ( $BS_e$ ) of each suspected  $ch_e$  where  $e \in E$  (each base station has a unique number assigned in  $NL_{DB}$  as exemplified in Table 3.1 in Chapter Three).
  - b) Frequencies:  $fmax_e$  and  $fmin_e$  of each  $ch_e$  ( $e \in E$ ). Since PUEA could be performed on part of  $ch_s$ , this means  $fmax_e$  and  $fmin_e$  may not be the same as  $fmax_s$  and  $fmin_s$ .
  - c) Utilisation: The exploitation times  $utti_e$  and dates  $utda_e$  of each  $ch_e$ .
- 4) *ATCK list*: PUED will compare both *EVA list* and *SUS list* to determine PUEAs. If any channel is found in both lists, it will be considered as PUEA. Therefore, let  $A$  be the number of attacked channels and the specification of the determined  $ch_e$  will be considered as  $ch_a$  ( $a \in A$ ). The specifications of  $A$  channels will be stored in a file known as *ATCK list* (referring to ‘Attack’). These specifications will include the following:
- a) Attacker base stations: The sequence number of the  $BS_a$  that are determined as PUEA committers.
  - b) Evacuated channels frequencies ( $fmax_s$  and  $fmin_s$ ).
  - c) Attacking channels frequencies ( $fmax_a$  and  $fmin_a$ ).
  - d) Utilisation and evacuated periods (i.e. ( $utti_s$ ,  $utda_s$ ) and ( $evti$ ,  $evda$ )).
  - e) Attack dates and times:  $utti_a$  and  $utda_a$  of each  $ch_a$ .

## 6.5 PUED in Action

### 6.5.1 Procedure and Time Sequence Processing of PUED

To understand the procedure of comparisons in PUED, we give a numerical example for a CRN that attempts to implement the algorithm. Note that the specifications of the channels in both the *EVA list* and *SUS list* do not represent any real data and are assumed in order to clarify PUED detection steps.

We suppose that CRN1 in location number 2 attempts to apply PUED. The procedure of implementing will be divided into four time processing sequences. Note the period of each time could be different and depends on processing information amount in each sequence. As depicted in Figure 6.2, the sequences are as follows:

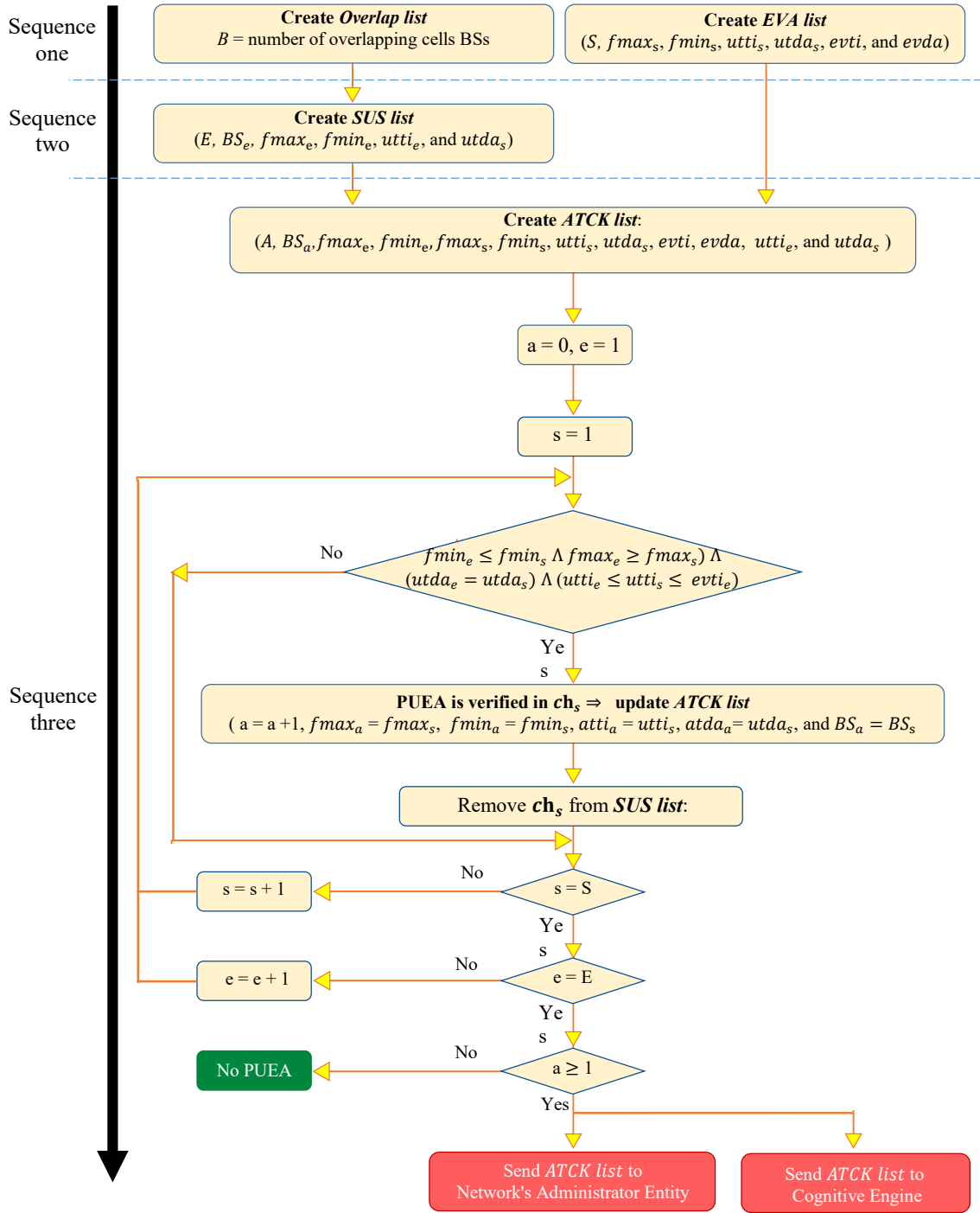


Figure 6.2: Time sequence processing of the PUED algorithm.

1) *Sequence one*: Here, PUED perform two tasks in parallel *Overlap list* and *EVA list*. **Firstly**, for *Overlap list*, we assume that our network has identified (from  $NL_{DB_2}$ ) the network coexists with seven cells (i.e.  $I=7$ ) belonging to a number of CRNs. However, usually, not all these cells are overlapping with each other. As listed in Table

6.1, let us assume the PUED has obtained in this level five cells (i.e.  $K=5$ ) overlapping as follows:  $BS_2, BS_3, BS_4, BS_6$ , and  $BS_7$ . **Secondly**, in the same time PUED will get the information of the *EVA list* from spectrum decision making component. Let us assume our network has evacuated seven channels ( $V = 7$ ) and five of them ( $S = 5$ ) need to be verified. Therefore, we assume the *EVA list* to be as in Table 6.2, where the channels have started to be utilised since 23:56:24:41 ( $= utti_s$ ) on 21/07/16 ( $= utda_s$ ) respectively until 00:02:32:10 ( $= evti$ ) on 22/07/16 ( $= evda$ ).

Table 6.1: Overlap list

Base Station No.	BS sequence in $NL_{DB_2}$
1	2
2	3
3	4
4	6
5	7

Table 6.2: EVA list of six evacuated channels need to be verified from any PUEA.

Channel No.	Evacuated channel		Utilisation		Evacuation	
	$f_{min}$	$f_{max}$	Date	Time	Date	Time
1	660	668	21/07/16	23:56:24:41	22/07/16	00:02:32:10
2	760	770				
3	2240	2250				
4	1310	1320				
5	1835	1845				

2) *Sequence two*: Accordingly, the algorithm in this level will check  $HS_{DB_2}$  for suspected channels utilised between ( $utti_s, utda_s$ ) and ( $evti, evda$ ) to determine the *SUS list*. Let us assume PUED determined six suspected channels ( $E=6$ ) in the *SUS list* as in Table 6.3.

Table 6.3: SUS list determined from  $HS_{DB_2}$ .

Channel No.	Base Station	Suspected channel		Utilisation	
		$f_{min}$	$f_{max}$	Date	Time
1	4	682	690	21/07/16	23:59:19:12
2	3	660	668	22/07/16	00:01:58:24
3	2	1460	1465	22/07/16	00:02:02:17
4	4	2240	2245	22/07/16	00:02:17:35
5	7	1310	1320	22/07/16	00:02:19:23
6	6	810	820	22/07/16	00:02:24:31

3) *Sequence three*: In this level, the *PUEA identifier component* will start to perform comparison steps between both *EVA list* and *SUS list* to determine *ATCK list* which can be as follows:

- a) *Frequencies Comparison Stage*: PUED proceeds to compare the frequencies of each channel from the *EVA list* with the channels of the *SUS list*. It is important to note that the attack could be performed either in the whole or part of the channel. Specifically, an entire band attack was committed by  $BS_3$  in the channel (660-668 MHz), while part band interference was committed on the channels (2240-2250 MHz) and (1310-1320 MHz), where  $BS_4$  and  $BS_7$  have attacked in the bands (2245-2250 MHz) and (1310-1318 MHz) respectively.
- b) *Time Comparison Stage*: In this step, the algorithm will verify the time of the above-identified channels. For instance, the band (660-668 MHz) was attacked by  $BS_3$  at (00:01:58:24) on (22/07/16). Additionally, the partial attacks on the channels (2240-2250 MHz) and (1310-1320 MHz) occurred at (00:02:17:35) on (22/07/16) and at (00:02:19:23) on (22/07/16) respectively. Accordingly, the details of the attacks are recorded in the *ATCK list* as illustrated in Table 6. 4



### 6.5.2 Outcome of PUED

Now, after determining the *ATCK list*, PUED will report the list to the following:

1) *Network's administrator entity*: a copy of the list will be sent to this entity in order to use it as evidence against the offender CRNs. Therefore, the list will be provided to the regulator. The regulator will then determine the identity of offender CRN(s) from  $NL_{DB_2}$  and take appropriate action based on self-coexistence rules (which is outside our research scope). Note that this step is very important to achieve our aim, which is to deter PUEA rather than merely detecting it.

2) *Network's cognitive engine*: A cognitive engine is an intelligent agent that facilitates situation awareness, adaptation, reasoning, learning, and planning [176]. Therefore, to avoid considering the PUEAs as normal PU activities, PUED periodically reports attack details to the network's Cognitive Engine. As a consequence, this will prevent devising unreliable models for the attacked channels. Finally, a pseudo code description of the PUED algorithm is presented in Table 6.5.

Channel No.	Attacker Base Station	Evacuated channel		Attack channel		Utilisation		Evacuation		Attack	
		$f_{min}$	$f_{max}$	$f_{min}$	$f_{max}$	Date	Time	Date	Time	Date	Time
1	3	660	668	660	668	21/07/16	23:56:24:41	22/07/16	00:02:32:10	22/07/16	00:01:58:24
2	4	2240	2250	2245	2250	22/07/16	00:00:41:37			22/07/16	00:02:17:35
3	7	1310	1320	1310	1318	22/07/16	00:00:41:37			22/07/16	00:02:19:23

Table 6.4 : ATCK list.

Table 6.5: PUED algorithm.

```

Algorithm: PUED algorithm
1:  Create EVA list
2:  Create SUS list
3:  Create ATCK list
4:  Let  $a = 0$  % counter for the attack channels %
5:  for  $e = 1$  to  $E$  do % counter for the suspected channels %
6:      for  $s = 1$  to  $S$  do % counter for the under-verifying channels %
7:          if  $(fmin_e \leq fmin_s \wedge fmax_e \geq fmax_s) \wedge (utda_e = utda_s) \wedge (utti_e \leq utti_s \leq evti_e)$ 
8:              then PUEA is verified in  $ch_s$ ;
9:               $fmax_a = fmax_s$ ;  $fmin_a = fmin_s$ ;  $atti_a = utti_s$ ;  $atda_a = utda_s$ ; and  $BS_a = BS_s$ ;
10:              $a = a + 1$ ;
11:             update ATCK list  $\leftarrow ch_a$ ;
12:             Remove  $ch_s$  from SUS list
13:          else no PUEA in  $ch_s$ 
14:          end if
15:      end for
16:  end for
17:  if  $a \geq 1$  then Output ATCK list to 1) Network's Administrator Entity
18:              2) Cognitive Engine
19:  else Output “ No PUEA ”
20:  end if

```

### 6.5.3 Complexity of PUED

Before leaving this section, it is important to mention that PUED can be implemented meanwhile the network is continuing its normal operation. However, we need to study the complexity of this algorithm. In computer science, a mathematical notation called ‘Big O’ is used to classify algorithms according to how their running time or space requirements grow as the input size grows [201]. Independent of any particular program or computer, it is important to quantify the number of operations or steps that our algorithm will require. First, we need to determine how long the algorithm takes, in terms of the size of its input. As clarified in the last subsection, PUED will consume three time sequences. Therefore our machine equation will consist of three terms. According to the Big O notation description:

- 1) The first time sequence is  $I$  which refers the number of repetitions to find  $K$  for the *Overlap list*.

2) The second time sequence is  $7E$ , where 7 represents **one** statement for comparing  $utti_s, utda_s, evti, evda$  and **six** for recording the items in the *SUS list* (i.e.  $BS_e, fmax_e, fmin_e, utti_e$ , and  $utda_s$ ).

3) The last term is  $12E(S - A)$ , where 12 represents the recorded items in the ATCK list (i.e.  $BS_a, fmax_e, fmin_e, fmax_s, fmin_s, utti_s, utda_s, evti, evda, utti_e$ , and  $utda_s$ ). Additionally,  $E(S - A)$  represents the number of iterations. (because when any channel is identified then its specification will be removed from the comparisons i.e. the number of iteration will be reduced from  $ES$  to  $E(S - A)$  times).

Since PUED aims to deter the number of attacks (i.e.  $A$ ), then, as  $A$  becomes less and as  $E$  and  $S$  get larger,  $A$  will become less significant to the final result. Therefore, when looking for an approximation for  $12E(S - A)$ , we can drop  $A$  and simply say the running time is  $12ES$ . Accordingly, our algorithm can be represented by  $K + 7E + 12ES$ . Therefore the Big O notation that would describe PUED is  $O(KES)$ .

## 6.6 How PUED Prevents PUEAs

Below, we will argue that the PUED algorithm will lead to deterring PUEAs. However, we first need to introduce the main crime prevention methods.

### 6.6.1 Crime Prevention Methods

According to the offence deterrence literature, there are two different crime prevention strategies [202]:

1) *Primary crime prevention*: Concerns the offence rather than the offender and is related to certain methods of localising the context of the criminality. Examples of this strategy are: a) *Caller ID Screening* (to show the numbers of nuisance calls); b) *CCTV surveillance* (to take images of offences taking place); and c) *Financial Penalties* (to emphasise the severity of punishment).

2) *Secondary Crime Prevention*: focuses on offenders rather than offence and seeks to prevent them from reoffending in the future: for example, centres for *Prisoner Health and Human Rights*, and *Programs of Rehabilitation*.

It is clear that PUED falls into the first type of crime strategies. Particularly, there are many similarities between our algorithm and CCTV systems. Therefore, in the next sub-section we will discuss this in detail.

### 6.6.2 PUED Operation as a CCTV Surveillance System

To understand which CCTV systems and which crime types are similar to PUED, we need to investigate CCTV systems. In the relevant literature, these systems can be classified according to [198]:

- 1) *Surveillance location*: Refers to whether it is used for government business or personal.
- 2) *Reasons for their use*: **Firstly**, criminal reasons (e.g. robbery, assault, criminal damage, endangering life, and vehicle theft). **Secondly**, non-criminal reasons (e.g. Employee training and education, part of emergency and disaster plan).
- 3) *Operation site*: Indicates whether the surveillance is in an open or closed area.
- 4) *Surveillance characteristics*: **Firstly**, technical types (e.g. Day/Night, Infrared/vision, and C-mount). **Secondly**, technical Network connection (e.g. Network/IP, wireless). **Thirdly**, viewshed (e.g. movement detection).

Therefore, PUED operation is very similar to the CCTV surveillance of visible crime in closed areas for the following reasons:

- 1) *Reason for use*: to determine PUEA commission, the PUED uses details similar to CCTV crime surveillance.
- 2) *Operation site*: since CogMnet has divided the country into specific size locations, thus it is similar to a CCTV system for crimes in closed areas.
- 3) *Clearly observable offence*: because all network utilisations are recorded in the databases and can be observed clearly by the CRNs. The best example of clearly visible crime is vehicle theft because other visible robberies cannot be as completely visible as vehicle theft at the point of commission. Therefore, we could now infer that our algoirthm outcome is expected to be like the CCTV systems for vehicle theft.

According to criminology writers, robust CCTV systems have shown a significant reduction in vehicle theft. As summarised in Table 6.6, to choose an appropriate sample, we compare PUED with a recent study of CCTV surveillance conducted at three

selected sites in Cincinnati, OH (small neighbourhood, apartment complexes, and multi-unit residential structures) [199]. For a one-year period evaluation (2012-2013) three-dimensional spatial analysis was used to evaluate the effectiveness of the CCTV system. The evaluation was conducted for the following crimes: robbery, assault, criminal damaging, endangering, and vehicle theft. The system can provide images of offences taking place, which is similar to our algorithm that can obtain the PUEA commission details. The study has shown a significant prevention of vehicle theft, reducing stealing rates by 80%. Consequently, we believe that PUED will achieve the same degree of improvement and deter 80% of PUEA.

It is of great importance to mention that CogMnet must enforce rules for the self-coexistence system that punish aggressive CRNs that may violate the rules. According to criminology writers, numerous studies have observed that financial penalties played a significant role in reducing crime and reoffending rates [200]. Hence, the deterrence rate of PUED can be increased further by severe financial fines.

Table 6.6: Comparison between PUED and CCTV's surveillance in [199].

Merit	CCTV surveillance	PUED algorithm	Similarity
Deterrence strategy	Primary crime prevention	Primary crime prevention	√
Reasons for its use	To prevent crime and provide increased safety.	To deter PUEA and provide reliable security coexistence.	√
Surveillance outcome	Shows the offender(s) committing the offence.	Shows how the CRN(s) are committing the PUEA.	√
Operation site	Selected cities with specified size.	Specified location size assigned by CogMnet.	√
Surveillance characteristics	Monitors approximately 1000ft from the camera at maximum; additionally, it can identify license plate numbers within a 300ft range and recognise objects and colour within a 1000ft.	Coverage of all utilisation by the existing and newly admitted CRNs from the databases	√
Surveillance period	Provides 24/7 surveillance.	24 Hours a Day.	√
Vandalism possibility	Yes	No	X
Continuous maintenance	Required	Not needed	X

## 6.7 Performance Evaluation

### 6.7.1 CRNs Reliability under PUEAs

In this subsection, we evaluate the network performance of the PUED using MATLAB R2016b (Version 9.1.0.441655). We investigate the influence of PUEA on the performance of SUs in terms of the Dropping ( $R_D$ ) and Blocking ( $R_B$ ) rates [203]:

$$R_D = \sum_{(x,y,z) \in \Omega} (\lambda_{PUS} P_{(x,y,z)} + P_{(md+PUEA)} \lambda_{PUEA} P_{(x,y,z)}) \quad (6.1)$$

$$R_B = \sum_{(x,y,z) \in \Omega} \lambda_{SUS} P_{(x,y,z)} \quad (6.2)$$

Where  $x$  and  $y$  represent the sum of PUs and PUEAs, and  $z$  denotes the number of SUs. Additionally,  $\lambda_{PUS}$ ,  $\lambda_{PUEAs}$  and  $\lambda_{SUS}$  are arrival rates of PUs, PUEAs and SUs respectively. In the equations  $P_{(md+PUEA)}$  represents probabilities of missing detection and PUEAs. According to CogMnet,  $P_{md}$  will be neglected because each CRN will verify its channels from  $RT_{DBI}$  before utilising them. Lastly,  $P_{(x,y,z)}$  is the steady state probability and  $\Omega$  is state aggregation.

Turning now to the experimental assumptions, we assume that there are ten available channels, where a PU can only take one channel. As summarised in Table 6.7, we adopt the arrival rates  $\lambda_{PUS}$ ,  $\lambda_{PUEAs}$  and  $\lambda_{SUS}$ , following Poisson process and assuming  $\lambda_{PUS}$  and  $\lambda_{SUS}$  as 0.2 and 0.1 respectively. When a PU arrives, SU will be dropped if the channels are all occupied or handed-off into a new idle channel. We assume the service times of both PUs and SUs follow exponential distribution with service rates of 0.4 and 0.2 respectively. Similarly, the service rate of PUEAs is assumed as 0.7. Lastly, in the experiments  $P_{(md+PUEA)}$  is taken as 0.2.

In Figures 6.2 and 6.3, we evaluated SUs' dropping and blocking rates according to different PUEAs arrival rates. Clearly, both figures show that dropping and blocking rates become higher as PUEA arrival rates increase, thus reducing the quality of service of SUs. In other words, reduction of dropping and blocking rates necessitates a decrease in attack arrival rates.

Table 6.7: Experimental assumptions.

Factors	Assigned value	
Available channels	10	
PUs arrival rate	0.2	Follow Poisson process
SUs arrival rate	0.1	
PUs services rate	0.4	Follow exponential distribution
SUs services rate	0.2	
PUEAs arrival rate	Variable	
PUEAs services rate	0.7	

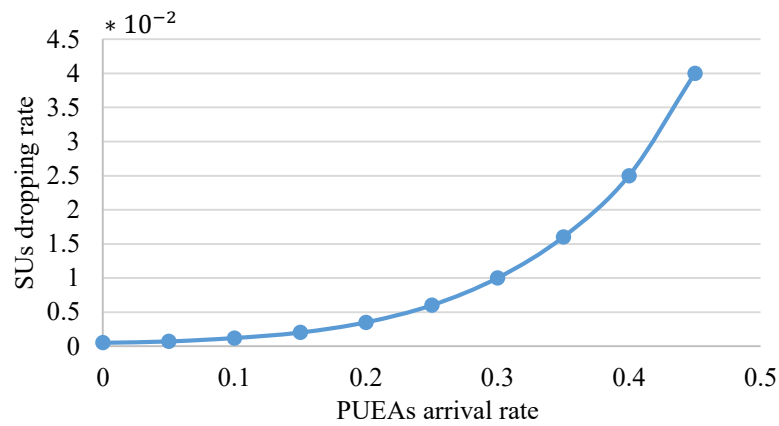


Figure 6.3: SUs dropping rate in different PUEAs arrival rates.

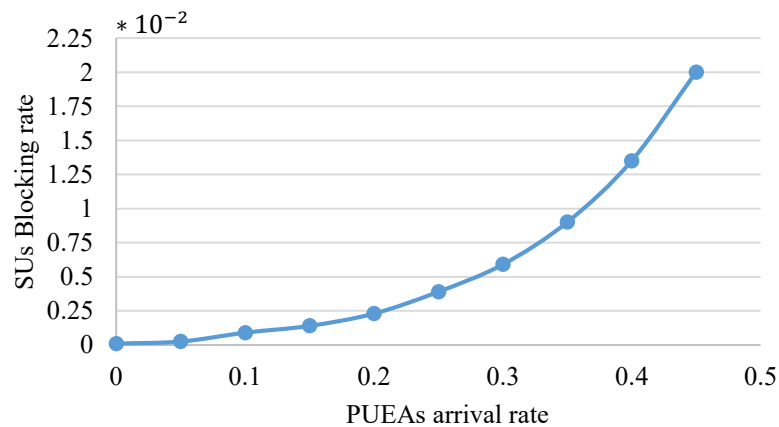


Figure 6.4: SUs blocking rate in different PUEAs arrival rates.

### 6.7.2 PUED Impact on CRNs Performance

In this subsection, we evaluate PUED by conducting simulations of an infrastructure-based CRN based on Vienna LTE-A Downlink System Level [220]. Table 6.8 presents the key CRN parameters used in our simulations. We considered our network to consist of a single site with a BS using an omnidirectional antenna allocated at the site centre with 25 m height. The coverage radius equals 500m, and CLSM discipline is applied.

Table 6.8: Simulation parameter settings.

Model parameter	Value
Channel type	Downlink
Tx Power	40 W
Tx antenna gain	15 dB
Rx antenna gain	0 dB
Rx beamwidth	Omni-directional
Number of channels	7
Bandwidth	1.4 MHz
Antenna type	CLSM 2x2 MIMO
Tx antenna height	25 m
Rx antenna height	1.5 m
Polarisation	Vertical
Modulation	Adaptive (QPSK, 16QAM, 64QAM)
Scheduler	Round Robin
SUs mobility	3 km/h (Pedestrian)
Number of SUs	Variable to test
Area of study	1 km <sup>2</sup>
Noise figure	8 dB
Noise density	-174 dBm/Hz
Traffic model	Full buffer



For simplicity, we assumed that seven available channels have the same bandwidth value as 1.4 MHz. A variable number of SUs is assumed, which are uniformly distributed inside the cell. We evaluated the network in three scenarios:

- 1) *No PUEAs*: represents no PUEA in the channels.
- 2) *Five PUEAs*: here, PUEAs are present in five channels.
- 3) *PUED Algorithm*: in this scenario, we apply our algorithm.

Fig. 6.4 shows the average number of allocated Resource Blocks (RBs) of each SU in the three scenarios. Firstly, regardless of how many SUs are in the CRN, the allocated RBs in the *Five PUEAs* case would decrease substantially compared with *No PUEAs*. One can observe from the figure that by applying our algorithm, the RBs of each user have increased significantly. Obviously, as the number of SUs increases, there is a significant decrease in amount of RBs per SU (Note that the round robin scheduler method is formulated in such a way that it shows the same number of RBs for each end user). Consequently, the transmission rate of each user will be greatly deteriorated.

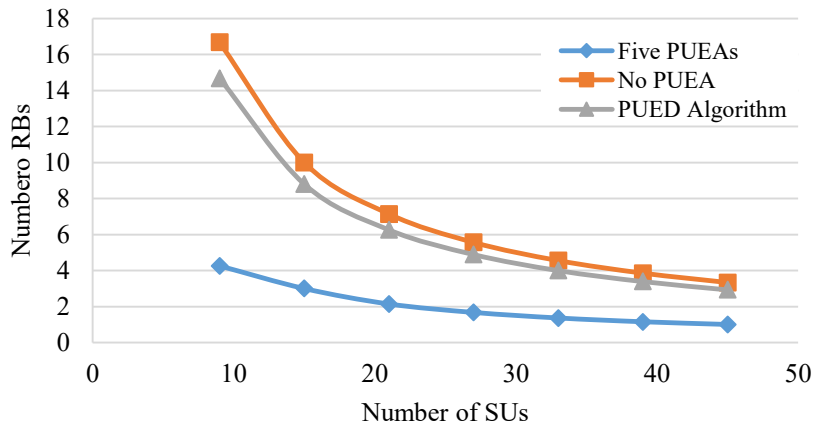


Figure 6.5: Average number of assigned RBs per SU.

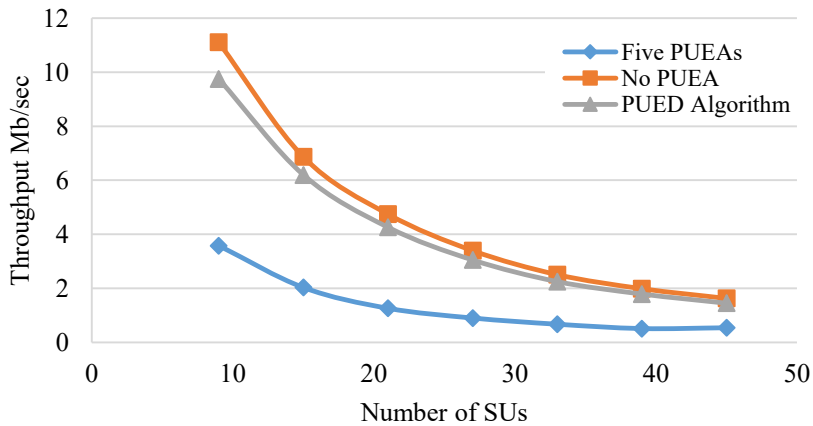


Figure 6.6: Average throughput per SUs.

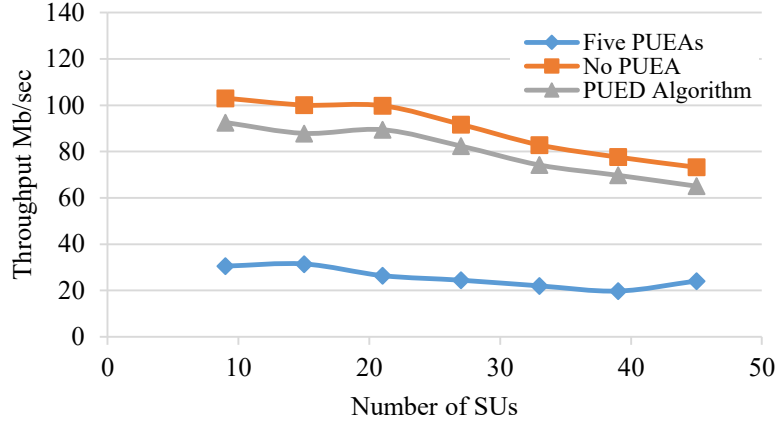


Figure 6.7: Overall network throughput.

Therefore, we evaluate in Figure 6.5 the average throughput of SUs in the three cases. It can be seen that the presence of PUED has reached the average data rates of the *No PUEAs* scenario. Additionally, it shows a significant improvement compared to the *Five PUEAs* case. The throughput degradation (in all cases) increases as the number of SUs increases as a consequence of reducing the number of RBs. In Figure 6.6, we compare the network throughput in all scenarios. One can clearly see that the *PUED Algorithm* scenario has led to a leap in the overall CRN throughput, thus improving the quality of service of the network.

## 6.8 Chapter Summary

In this chapter, a PUEA deterrent algorithm, namely PUED, has been proposed. PUED enables CRNs to determine the offender network and attacks' details. PUED is implemented by *PUEA Identifier Component* by one of RCNC engines. Like eye witness crime prevention schemes, particularly CCTV surveillance, the PUED report's *ATCK list* contains the full details about the offender CRN(s) to be used as evidence against the adversary CRNs. We believe that PUED will contribute to the prevention of PUEAs in the same way as CCTV deters crimes. Additionally, another important role for PUED is improving CRNs' ability to devise reliable models for the attacked channels to avoid considering PUEAs as real PU activities

# Chapter Seven: Conclusions and Future Work

*What we call the beginning is often the end.  
And to make an end is to make a beginning.  
The end is where we start from.*

*T. S. Eliot*

## 7.1 Introduction

Although the CRNs area is relatively new, a large volume of research has been conducted in this area in the last decade by standardisation bodies, and academic researchers. The ultimate goal of CRNs is to utilise spectrum bands efficiently. Additionally, establishing new wireless communication networks contributes to wide social and business consequences as smart devices displace traditional cellular phones. However, the deployment of a commercial CRN is yet to emerge. Since CRNs are unlicensed, they pose enormous challenges in their spectrum sharing (Incumbent and Self-Coexistence). The focus of this research was how to avoid critical self-coexistence issues in infrastructure based CRNs due to any intentional and unintentional behaviour of other CRNs. While the existing algorithms and schemes are promising, they are not able to prevent the attacks. In this chapter, we close the thesis by summarising our achievements and describing the possible areas for extending our work in the future.

## 7.2 Outcomes of the Research Study

In this section, we highlight the main theme of this research study and show how it has succeeded in answering research problems. As illustrated in Figure 7.1, the key research objectives have been achieved as follows.

### 7.2.1 Identifying Research Problems

Here, we summarise how we identified the key research problems.

1) *Survey 1*: In our first step to identify research problems accurately, a survey was presented [10]. In this step, we investigated the achievements, challenges, open research issues and future trends in CRNs spectrum sharing. This survey has introduced us to opportunities to increase utilisation of the residual spectrum.

2) *Survey 2*: In this stage, we carried out an extensive search in surveys in Cognitive Radio context to identify research problems. We found that the existing surveys are concerned with: a) *A particular QoS objective*; b) *technical development in one CRNs component*; c) *A function of a CRN component*; d) *Investigating various security challenges*; e) *Security challenges*; f) *Developments in a CR based application*; and j) *PHY or MAC layers*. Based on these categories, we decided to obtain the QoS provisioning approaches of CRN components. Therefore, we presented in [46] an up-to-date comprehensive survey of recent improvements in these approaches. To avoid confusing the reader with our main research problem, and due to the extensive nature of the topic, the main part of the survey is presented in Chapter 2. However, we would encourage readers to go through the survey to understand the issues and future directions in the CRNs context. From the survey, we found that to enable efficient communications, CRNs need to address two types of coexistence issues: Incumbent-coexistence, and Self-coexistence. We also found that while Incumbent coexistence has been effectively addressed in the literature, critical issues are still open in self-coexistence.

3) *Survey 3*: In our third survey [52], we investigated the impact of CRNs coexisting issues. We found that, the CRNs compel each other intentionally and unintentionally to lose utilising spectrum opportunities. In the unintentional category, CRNs are forced to vacate their spectrum bands due to: a) *Missed spectrum detection* because so far the spectrum sensing is imperfect; b) *Reduction in useful spectrum bands availability* because of expected rapid increasing of CRNs once they started to deploy (i.e. *need to*

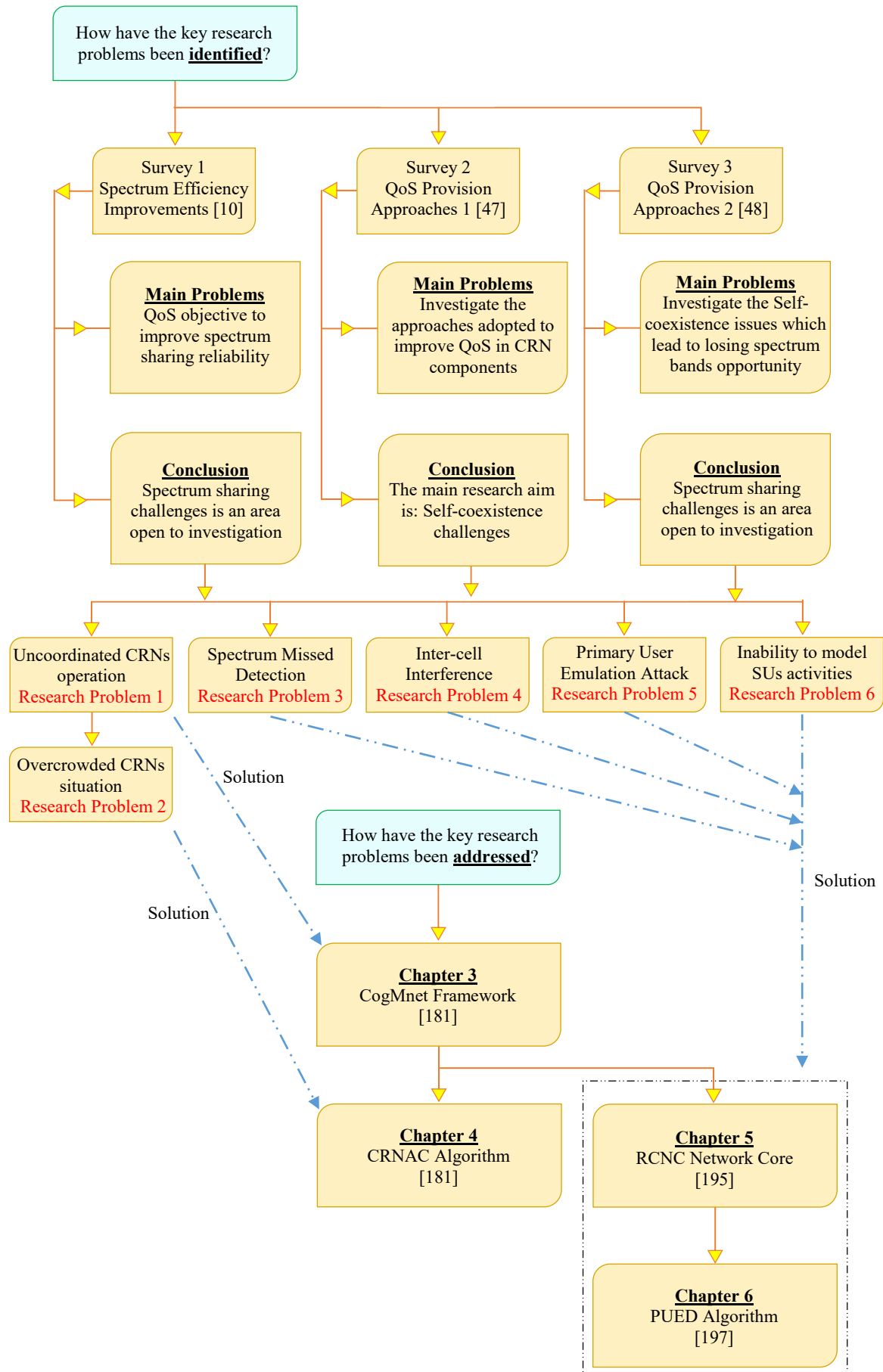


Figure 7.1: The outline of the research process and thesis structure.

*assign number of CRNs*); c) *Inter-Cell Interference* among neighbouring CRNs, since no network can determine exactly what other networks are in the vicinity and what they are utilising; and d) *Unreliable modelling for the spectrum* because when a CRN performs a sensing task, the network is unable to recognise whether the occupied channels are underutilised by other CRNs (i.e. *Inability of Modelling SUs activity*). In addition, we identified a serious issue where a selfish/malicious CRN may cause other CRNs to vacate channels by emulating PUs characteristics (i.e. *Primary User Emulation Attack*).

4) *Step 4 Key solution*: As a result of these three surveys and after an extensive search on these five problems we found that a key solution to these problems could be an internetwork management tool that coordinates CRNs spectrum sharing. The administration must coordinate all CRNs by enforcing certain rules that can contribute to tackling our challenges. Therefore our start point will be in managing CRNs (i.e. *propose internetwork framework*). Now we have identified our problems, the next subsection will describe how we have addressed each challenge.

## 7.2.2 Addressing Research Problems

As a result of these conclusions, Chapters 3, 4, 5, and 6 have considered our research problem. Each issue has been addressed as follows:

1) Chapter 3 has provided an internetwork framework CogMnet to manage spectrum sharing among centralised CRNs. CogMnet must be administrated by national regulators. CogMnet divides the whole area, let us say the country, into  $L$  locations. It then dedicates a real-time database for each location to record CRNs utilisations in real time. As exemplified in chapter 3, each database includes three storage units: Networks Locations storage; Real Time storage; and Historical storage unit. **Firstly**, Networks Locations storage is dedicated to storing the specifications of the existing networks in terms of BSs' position, status, and coverage area. To preserve the privacy of the networks utilisation, only the regulator has exclusive right to observe the networks' identity. Therefore, each BS has a sequence number that does not reflect to which network it may belong. Also, the table must be updated for any change. **Secondly**, Real-time storage unit is used to recording in real-time the transmission parameters of the channels that are in use by the networks. Therefore, each network must send its channels' details immediately after starting to utilise them. If any channel is evacuated, then its

specifications will be removed from this unit to historical storage. **Lastly**, the historical storage unit is a large capacity storage dedicated to recording channels' specifications after they have been evacuated. It is similar to the Real-time unit, except here the evacuation date and time are inserted. We, therefore, concluded that CogMnet can contribute to the following:

- a) Assign the maximum number of CRNs allowed in any location.
- b) As long as networks' utilisations are recorded, so no CRN may try to perform PUEA because when an attack occurs, it would be very easy to determine the attacker network.
- c) By utilising CogMnet databases, Inter-cell Interference issue will be eliminated because all CRNs will know what frequencies are in use in their vicinities.
- d) By exploiting the historical storage unit, CRNs will be able to model SUs activity, which is very important to devise a reliable model for the spectrum. To the best of our knowledge, this is the first piece of work that enables modelling of SUs activity.
- e) Improve sensing efficiency by exploiting real-time storage to remove the occupied channels from the sensing task.
- f) As long as networks' utilisations are recorded, the regulators will guarantee that no network will utilise non-permitted channels (For example security and military channels).
- g) The overseeing will avoid CRNs being exploited by malicious or terrorist groups.
- h) By exploiting historical storage units, CRNs can determine candidate places that the network may plan to extend to.
- i) CogMnet will guarantee a new income for the regulators.

2) To demonstrate the effectiveness of CogMnet, our second contribution in Chapter 4 was CRNAC, the first network admission algorithm in the CRN context. The admission steps of the algorithm can be summarised very briefly in three steps: In the first step the regulator will calculate the following: spectrum availability, the utilisation of each network and assign the highest performance network as a reference network for

admitting, and, calculate the scalability of both PNs and existing CRNs. The second step proposes a spectrum guard quantity used for avoiding a saturated spectrum situation. Finally, apply the proposed admission equations. CRNAC has been evaluated using MATLAB. Since we do not have counterparts to prove the superiority of our algorithm, therefore we evaluated the admission equation by changing the selection of highest performance network to be based on five cases. When we compared the spectrum required by existing networks with the admission spectrum of each case, we found that the admission spectrum of these cases is not sufficient to operate the newly added networks as well as the existing ones. Therefore, we conclude:

- a) CRNAC admission constraints must be adopted carefully to avoid an overcrowded CRNs situation because spectrum bands availability differs from a country to another.
- b) The constraints must be updated according to the CRNs usage.
- 3) According to CogMnet, CRNs have three environment resources rather than two. **Firstly**, the Spectrum Sensing Component, but it is not perfect. **Secondly**, Geolocation or SAS databases, but each one is restricted to a specific band (TV and 3550-3700 Mhz respectively) and available in popular countries only. **Thirdly**, CogMnet database. Accordingly, CRN core architecture must be modified to be able to utilise these three resources instead of two. Therefore in Chapter 5, we proposed a framework of a new infrastructure-based CRN, RCNC, for an efficient solution to prevent four different critical CRNs' self-coexistence issues: Spectrum misdetection; Inter-cell Interference; PUEA; enabling modelling of SUs activity. In addition to all of the above, RCNC is expected to improve networks' spectrum sensing efficiency and plans to extend network coverage. To perform these tasks, RCNC utilises and integrates the information of spectrum sensing, geolocation databases, and CogMnet databases. From the conducted simulation results, we see that RCNC is able to overcome self-coexistence problems and prevent the networks performance deterioration. We, therefore, conclude this chapter with two remarks:

- a) *RCNC in all CRNs*: If we want to guarantee reliable self-coexistence among infrastructure-based CRN types, then we have to consider incorporating RCNC in their design.



- b) *Official adoption of CogMnet*: In this research, we have emphasised the importance of official adoption of CogMnet, as this will bring benefits for both CRNs and regulators. Additionally, we believe that it will encourage the licensing networks to offer secondary services (as CRNs) in addition to their services.
- 4) In Chapter 6, PUEA deterrent algorithm, PUED, has been proposed. PUED must be implemented by PUEA Identifier Component in RCNC after every spectrum handing off. PUED enables CRNs to determine the offender network and attacks' details. This information can be used as evidence against the adversary CRNs. In the criminology literature, we found many similarities between PUED operation and CCTV surveillance systems which are used to deter crimes. Likewise, we believe that PUED will contribute to the prevention of PUEAs. Additionally, PUED will help the CRNs to devise reliable models for the attacked channels to avoid considering PUEAs as real PU activities.
- We, therefore, conclude this chapter by emphasising that it is necessary to incorporate PUED in all CRNs design.

## 7.3 Future Work

As we have shown in previous chapters, various potential areas for future research have been recognised as follows.

### 7.3.1 CogMnet Implementation

As a result of Chapter 3, to design CogMnet, it is essential for the regulators to allocate all implementation requirements appropriately. Therefore, it is important to investigate in depth the implementation issues of CogMnet. For this purpose and in order to market CogMnet officially, our next step is to seek for collaboration with a technology company.

### 7.3.2 RCNC Merits

In Chapter 5, a need was identified for verification to confirm that some benefit can be obtained by RCNC. Therefore, in the future, we plan to conduct more experiments to validate both *Sensing Supporter* in terms of power consumption. Very briefly, the component allows the network to check Real-time storage units to determine the channels that are already under-utilised by overlapping CRNs. The listed channels will

be reported to the Spectrum sensing component. Here, if the CRN uses the filter-bank wideband detection [209], removing some channels will lead to reducing the number of operated filters, thus reducing power consumption. In addition, we intend to modify RCNC capabilities to meet the false alarm challenge which (as described in Chapter 2) is defined as the detector of spectrum sensing component indicating that the channel is occupied when it is not.

### 7.3.3 Adopt RCNC in IEEE 802.22

As part of our future work, we intend to extend our study for modifying IEEE 802.22 standard according to RCNC. Briefly, IEEE 802.22 WRAN is the first standard exploiting CR based physical (PHY) and medium access control (MAC) layers to provide wireless broadband services in remote rural areas. By utilising vacant portions TVWS band, WRAN comprises a single-hop cell (covers an area of radius 33 km) coordinated by a Base Station (BS) that serves SUs. The end-user is called Consumer Premise Equipment (CPE) and represents household; hence, they are stationary nodes.

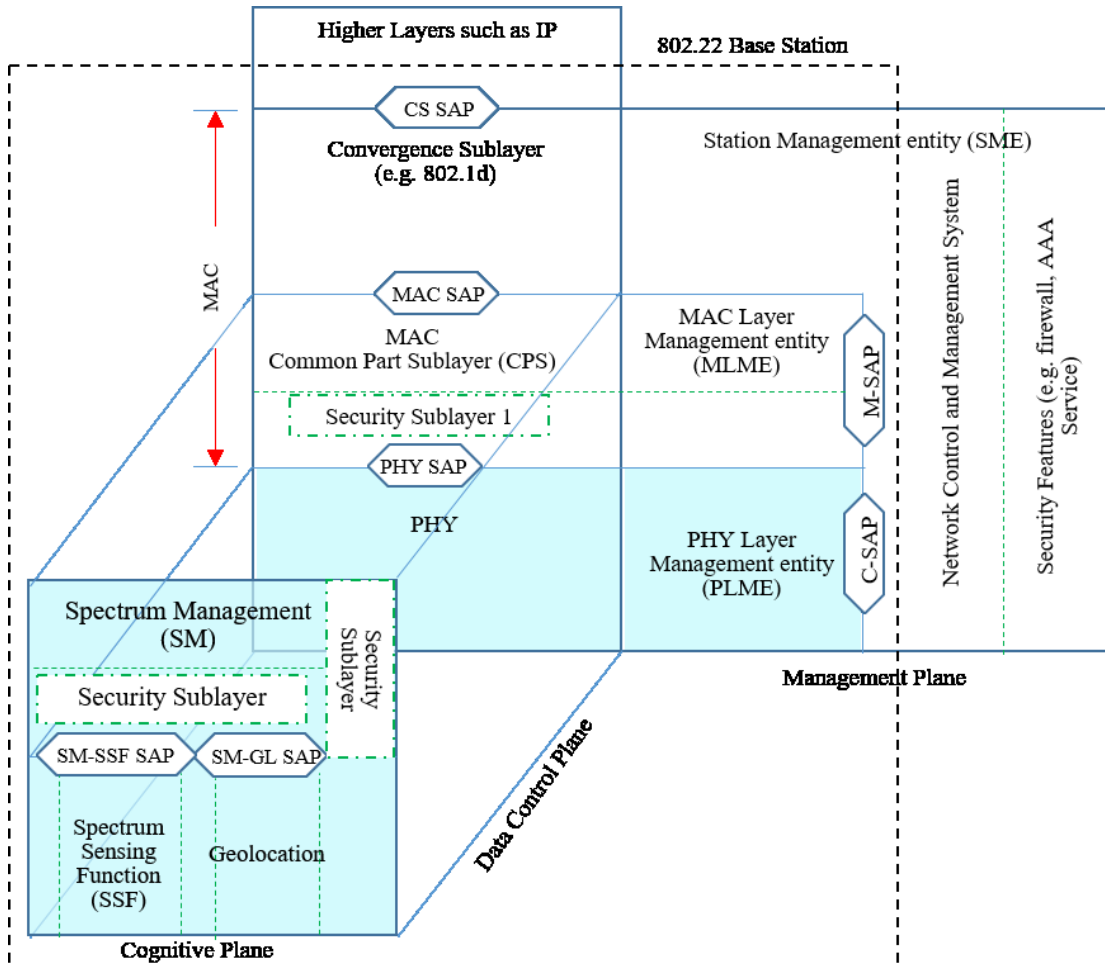


Figure 7.2: A cognitive radio interface diagram for the IEEE 802.22 standard

In TVWS band, PUs' activities are classified into: wireless microphone, analogue TV broadcasting and Digital TV broadcasting (DVB). To ensure the protection of primary broadcast system and to maximise the benefit of usable radio spectrum both BS and its associated CPEs use two detection techniques: *spectrum sensing*; and *geolocation databases*. Figure 7.2 depicts the cognitive radio interface diagram for the IEEE 802.22 standard which is called Protocol Reference Model (PRM). PRM defines system architecture, the functions of the blocks, and their interactions. Specifically, PRM divides the system into: management, cognitive, and data/control planes. In the management plane, the Spectrum Manager (SP) receives its information of incumbents' presence and location from both spectrum sensing function (SSF) and geolocation function. The SM function at the base station makes the intelligence and the decision making capabilities (i.e. decisions on transmission of the information signals). On the other hand, the SM at the CPE is known as Spectrum Automation (SA). Security sub-layers are inserted among Service Access points (SAP) to protect non-cognitive as well as cognitive functions [13]. Accordingly, the blue coloured areas need to be modified to adopt RCNC capabilities.

Finally, we close this thesis and we believe that this research study will persuade the regulators to start thinking seriously about our vision of coordinating CRNs operation.

# Appendix A

MATLAB codes of CRNAC Algorithm:

```
% Algorithm of Network Admission Control for Admitting CRNs%
disp ('This Programme is CRNAC algorithm')
disp ('CRNs Admission Control and Maximum Allowed CRNs')
Iterations = input ('Input Iteration for the programme= ');
Comp = Iterations;
SetIt = Iterations;
NO = 0; % Number of Not allowed during the Iterations%
ACC = 0; % Number of Acceptance during of the Iteration%
Z = 0; % Total of allowed Networks in whole the Iteration%
AvZ = 0; % Average of the allowed CRNs%
MinimumAvailableSpectrum= input('Input Minimum Available Spectrum
Please = ');
MaximumAvailableSpectrum= input('Input Maximum Available Spectrum
Please = ');
Tests = input('Input Number of Tests= ');
N = input ('Input Number of Existing CRNs Please = ');
Toset= N;
Nomore = N;
if (N==1)
    Min1= input ('Input Minimum Utilisation of CRN1= ');
    Max1= input ('Input Maximum Utilisation of CRN1= ');
    ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
    ScalabilityTOT = ScalabilityCRN1;
    gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
    DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==2)
    Min1= input ('Input Minimum Utilisation of CRN1 = ');
    Max1= input ('Input Maximum Utilisation of CRN1 = ');
    Min2= input ('Input Minimum Utilisation of CRN2 = ');
    Max2= input ('Input Maximum Utilisation of CRN2 = ');
    ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
    ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
    ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 ;
    gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
    DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==3)
    Min1= input ('Input Minimum Utilisation of CRN1 = ');
    Max1= input ('Input Maximum Utilisation of CRN1 = ');
    Min2= input ('Input Minimum Utilisation of CRN2 = ');
    Max2= input ('Input Maximum Utilisation of CRN2 = ');
    Min3= input ('Input Minimum Utilisation of CRN3 = ');
    Max3= input ('Input Maximum Utilisation of CRN3 = ');
    ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
    ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
    ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
    ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3;
```

```
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==4)
Min1= input ('Input Minimum Utilisation of CRN1 = ');
Max1= input ('Input Maximum Utilisation of CRN1 = ');
Min2= input ('Input Minimum Utilisation of CRN2 = ');
Max2= input ('Input Maximum Utilisation of CRN2 = ');
Min3= input ('Input Minimum Utilisation of CRN3 = ');
Max3= input ('Input Maximum Utilisation of CRN3 = ');
Min4= input ('Input Minimum Utilisation of CRN4 = ');
Max4= input ('Input Maximum Utilisation of CRN4 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4;
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==5)
Min1= input ('Input Minimum Utilisation of CRN1 = ');
Max1= input ('Input Maximum Utilisation of CRN1 = ');
Min2= input ('Input Minimum Utilisation of CRN2 = ');
Max2= input ('Input Maximum Utilisation of CRN2 = ');
Min3= input ('Input Minimum Utilisation of CRN3 = ');
Max3= input ('Input Maximum Utilisation of CRN3 = ');
Min4= input ('Input Minimum Utilisation of CRN4 = ');
Max4= input ('Input Maximum Utilisation of CRN4 = ');
Min5= input ('Input Minimum Utilisation of CRN5 = ');
Max5= input ('Input Maximum Utilisation of CRN5 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5;
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
utilising of Primary Networks = ');
end
if (N==6)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
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ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6;
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Expected Promotion in Spectrum Utilising
of Primary Networks = ');
end
if (N==7)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7;
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==8)
Min1= input ('Input minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
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ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8;
    gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
    DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==9)
    Min1= input ('Input Minimum Utilisation CRN1 = ');
    Max1= input ('Input Maximum Utilisation CRN1 = ');
    Min2= input ('Input Minimum Utilisation CRN2 = ');
    Max2= input ('Input Maximum Utilisation CRN2 = ');
    Min3= input ('Input Minimum Utilisation CRN3 = ');
    Max3= input ('Input Maximum Utilisation CRN3 = ');
    Min4= input ('Input Minimum Utilisation CRN4 = ');
    Max4= input ('Input Maximum Utilisation CRN4 = ');
    Min5= input ('Input Minimum Utilisation CRN5 = ');
    Max5= input ('Input Maximum Utilisation CRN5 = ');
    Min6= input ('Input Minimum Utilisation CRN6 = ');
    Max6= input ('Input Maximum Utilisation CRN6 = ');
    Min7= input ('Input Minimum Utilisation CRN7 = ');
    Max7= input ('Input Maximum Utilisation CRN7 = ');
    Min8= input ('Input Minimum Utilisation CRN8 = ');
    Max8= input ('Input Maximum Utilisation CRN8 = ');
    Min9= input ('Input Minimum Utilisation CRN9 = ');
    Max9= input ('Input Maximum Utilisation CRN9 = ');
    ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
    ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
    ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
    ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
    ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
    ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
    ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
    ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
    ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
    ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9;
    gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
    DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==10)
    Min1= input ('Input Minimum Utilisation CRN1 = ');
    Max1= input ('Input Maximum Utilisation CRN1 = ');
    Min2= input ('Input Minimum Utilisation CRN2 = ');
    Max2= input ('Input Maximum Utilisation CRN2 = ');
    Min3= input ('Input Minimum Utilisation CRN3 = ');
    Max3= input ('Input Maximum Utilisation CRN3 = ');
    Min4= input ('Input Minimum Utilisation CRN4 = ');
    Max4= input ('Input Maximum Utilisation CRN4 = ');
    Min5= input ('Input Minimum Utilisation CRN5 = ');
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Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
Min9= input ('Input Minimum Utilisation CRN9 = ');
Max9= input ('Input Maximum Utilisation CRN9 = ');
Min10= input ('Input Minimum Utilisation CRN10 = ');
Max10= input ('Input Maximum Utilisation CRN10 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
ScalabilityCRN10 = input('Input the Scalability of CRN10 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9 +
ScalabilityCRN10;
gardspectrum = input ('The Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('The Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==11)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
Min9= input ('Input Minimum Utilisation CRN9 = ');
Max9= input ('Input Maximum Utilisation CRN9 = ');
Min10= input ('Input Minimum Utilisation CRN10 = ');
Max10= input ('Input Maximum Utilisation CRN10 = ');
Min11= input ('Input Minimum Utilisation CRN11 = ');
Max11= input ('Input Maximum Utilisation CRN11 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
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ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
ScalabilityCRN10 = input('Input the Scalability of CRN10 = ');
ScalabilityCRN11 = input('Input the Scalability of CRN11 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9 +
ScalabilityCRN10 + ScalabilityCRN11;
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
ccase = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==12)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
Min9= input ('Input Minimum Utilisation CRN9 = ');
Max9= input ('Input Maximum Utilisation CRN9 = ');
Min10= input ('Input Minimum Utilisation CRN10 = ');
Max10= input ('Input Maximum Utilisation CRN10 = ');
Min11= input ('Input Minimum Utilisation CRN11 = ');
Max11= input ('Input Maximum Utilisation CRN11 = ');
Min12= input ('Input Minimum Utilisation CRN12 = ');
Max12= input ('Input Maximum Utilisation CRN12 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
ScalabilityCRN10 = input('Input the Scalability of CRN10 = ');
ScalabilityCRN11 = input('Input the Scalability of CRN11 = ');
ScalabilityCRN12 = input('Input the Scalability of CRN12 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9 +
ScalabilityCRN10 + ScalabilityCRN11 + ScalabilityCRN12;
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==13)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
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Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
Min9= input ('Input Minimum Utilisation CRN9 = ');
Max9= input ('Input Maximum Utilisation CRN9 = ');
Min10= input ('Input Minimum Utilisation CRN10 = ');
Max10= input ('Input Maximum Utilisation CRN10 = ');
Min11= input ('Input Minimum Utilisation CRN11 = ');
Max11= input ('Input Maximum Utilisation CRN11 = ');
Min12= input ('Input Minimum Utilisation CRN12 = ');
Max12= input ('Input Maximum Utilisation CRN12 = ');
Min13= input ('Input Minimum Utilisation CRN13 = ');
Max13= input ('Input Maximum Utilisation CRN13 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
ScalabilityCRN10 = input('Input the Scalability of CRN10 = ');
ScalabilityCRN11 = input('Input the Scalability of CRN11 = ');
ScalabilityCRN12 = input('Input the Scalability of CRN12 = ');
ScalabilityCRN13 = input('Input the Scalability of CRN13 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9 +
ScalabilityCRN10 + ScalabilityCRN11 + ScalabilityCRN12 +
ScalabilityCRN13;
guardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if(N==14)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
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Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
Min9= input ('Input Minimum Utilisation CRN9 = ');
Max9= input ('Input Maximum Utilisation CRN9 = ');
Min10= input ('Input Minimum Utilisation CRN10 = ');
Max10= input ('Input Maximum Utilisation CRN10 = ');
Min11= input ('Input Minimum Utilisation CRN11 = ');
Max11= input ('Input Maximum Utilisation CRN11 = ');
Min12= input ('Input Minimum Utilisation CRN12 = ');
Max12= input ('Input Maximum Utilisation CRN12 = ');
Min13= input ('Input Minimum Utilisation CRN13 = ');
Max13= input ('Input Maximum Utilisation CRN13 = ');
Min14= input ('Input Minimum Utilisation CRN14 = ');
Max14= input ('Input Maximum Utilisation CRN14 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
ScalabilityCRN10 = input('Input the Scalability of CRN10 = ');
ScalabilityCRN11 = input('Input the Scalability of CRN11 = ');
ScalabilityCRN12 = input('Input the Scalability of CRN12 = ');
ScalabilityCRN13 = input('Input the Scalability of CRN13 = ');
ScalabilityCRN14 = input('Input the Scalability of CRN14 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9 +
ScalabilityCRN10 + ScalabilityCRN11 + ScalabilityCRN12 +
ScalabilityCRN13 + ScalabilityCRN14;
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if(N==15)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
Min9= input ('Input Minimum Utilisation CRN9 = ');
Max9= input ('Input Maximum Utilisation CRN9 = ');
Min10= input ('Input Minimum Utilisation CRN10 = ');
Max10= input ('Input Maximum Utilisation CRN10 = ');
Min11= input ('Input Minimum Utilisation CRN11 = ');
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Max11= input ('Input Maximum Utilisation CRN11 = ');
Min12= input ('Input Minimum Utilisation CRN12 = ');
Max12= input ('Input Maximum Utilisation CRN12 = ');
Min13= input ('Input Minimum Utilisation CRN13 = ');
Max13= input ('Input Maximum Utilisation CRN13 = ');
Min14= input ('Input Minimum Utilisation CRN14 = ');
Max14= input ('Input Maximum Utilisation CRN14 = ');
Min15= input ('Input Minimum Utilisation CRN15 = ');
Max15= input ('Input Maximum Utilisation CRN15 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
ScalabilityCRN10 = input('Input the Scalability of CRN10 = ');
ScalabilityCRN11 = input('Input the Scalability of CRN11 = ');
ScalabilityCRN12 = input('Input the Scalability of CRN12 = ');
ScalabilityCRN13 = input('Input the Scalability of CRN13 = ');
ScalabilityCRN14 = input('Input the Scalability of CRN14 = ');
ScalabilityCRN15 = input('Input the Scalability of CRN15 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9 +
ScalabilityCRN10 + ScalabilityCRN11 + ScalabilityCRN12 +
ScalabilityCRN13 + ScalabilityCRN14 + ScalabilityCRN15;
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==16)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
Min9= input ('Input Minimum Utilisation CRN9 = ');
Max9= input ('Input Maximum Utilisation CRN9 = ');
Min10= input ('Input Minimum Utilisation CRN10 = ');
Max10= input ('Input Maximum Utilisation CRN10 = ');
Min11= input ('Input Minimum Utilisation CRN11 = ');
Max11= input ('Input Maximum Utilisation CRN11 = ');
Min12= input ('Input Minimum Utilisation CRN12 = ');
Max12= input ('Input Maximum Utilisation CRN12 = ');
Min13= input ('Input Minimum Utilisation CRN13 = ');
Max13= input ('Input Maximum Utilisation CRN13 = ');
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Min14= input ('Input Minimum Utilisation CRN14 = ');
Max14= input ('Input Maximum Utilisation CRN14 = ');
Min15= input ('Input Minimum Utilisation CRN15 = ');
Max15= input ('Input Maximum Utilisation CRN15 = ');
Min16= input ('Input Minimum Utilisation CRN16 = ');
Max16= input ('Input Maximum Utilisation CRN16 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
ScalabilityCRN10 = input('Input the Scalability of CRN10 = ');
ScalabilityCRN11 = input('Input the Scalability of CRN11 = ');
ScalabilityCRN12 = input('Input the Scalability of CRN12 = ');
ScalabilityCRN13 = input('Input the Scalability of CRN13 = ');
ScalabilityCRN14 = input('Input the Scalability of CRN14 = ');
ScalabilityCRN15 = input('Input the Scalability of CRN15 = ');
ScalabilityCRN16 = input('Input the Scalability of CRN16 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9 +
ScalabilityCRN10 + ScalabilityCRN11 + ScalabilityCRN12 +
ScalabilityCRN13 + ScalabilityCRN14 + ScalabilityCRN15 +
ScalabilityCRN16;
guardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==17)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
Min9= input ('Input Minimum Utilisation CRN9 = ');
Max9= input ('Input Maximum Utilisation CRN9 = ');
Min10= input ('Input Minimum Utilisation CRN10 = ');
Max10= input ('Input Maximum Utilisation CRN10 = ');
Min11= input ('Input Minimum Utilisation CRN11 = ');
Max11= input ('Input Maximum Utilisation CRN11 = ');
Min12= input ('Input Minimum Utilisation CRN12 = ');
Max12= input ('Input Maximum Utilisation CRN12 = ');
Min13= input ('Input Minimum Utilisation CRN13 = ');
Max13= input ('Input Maximum Utilisation CRN13 = ');
Min14= input ('Input Minimum Utilisation CRN14 = ');
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Max14= input ('Input Maximum Utilisation CRN14 = ');
Min15= input ('Input Minimum Utilisation CRN15 = ');
Max15= input ('Input Maximum Utilisation CRN15 = ');
Min16= input ('Input Minimum Utilisation CRN16 = ');
Max16= input ('Input Maximum Utilisation CRN16 = ');
Min17= input ('Input Minimum Utilisation CRN17 = ');
Max17= input ('Input Maximum Utilisation CRN17 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
ScalabilityCRN10 = input('Input the Scalability of CRN10 = ');
ScalabilityCRN11 = input('Input the Scalability of CRN11 = ');
ScalabilityCRN12 = input('Input the Scalability of CRN12 = ');
ScalabilityCRN13 = input('Input the Scalability of CRN13 = ');
ScalabilityCRN14 = input('Input the Scalability of CRN14 = ');
ScalabilityCRN15 = input('Input the Scalability of CRN15 = ');
ScalabilityCRN16 = input('Input the Scalability of CRN16 = ');
ScalabilityCRN17 = input('Input the Scalability of CRN17 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9 +
ScalabilityCRN10 + ScalabilityCRN11 + ScalabilityCRN12 +
ScalabilityCRN13 + ScalabilityCRN14 + ScalabilityCRN15 +
ScalabilityCRN16 + ScalabilityCRN17;
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==18)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
Min9= input ('Input Minimum Utilisation CRN9 = ');
Max9= input ('Input Maximum Utilisation CRN9 = ');
Min10= input ('Input Minimum Utilisation CRN10 = ');
Max10= input ('Input Maximum Utilisation CRN10 = ');
Min11= input ('Input Minimum Utilisation CRN11 = ');
Max11= input ('Input Maximum Utilisation CRN11 = ');
Min12= input ('Input Minimum Utilisation CRN12 = ');
Max12= input ('Input Maximum Utilisation CRN12 = ');
Min13= input ('Input Minimum Utilisation CRN13 = ');
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Max13= input ('Input Maximum Utilisation CRN13 = ');
Min14= input ('Input Minimum Utilisation CRN14 = ');
Max14= input ('Input Maximum Utilisation CRN14 = ');
Min15= input ('Input Minimum Utilisation CRN15 = ');
Max15= input ('Input Maximum Utilisation CRN15 = ');
Min16= input ('Input Minimum Utilisation CRN16 = ');
Max16= input ('Input Maximum Utilisation CRN16 = ');
Min17= input ('Input Minimum Utilisation CRN17 = ');
Max17= input ('Input Maximum Utilisation CRN17 = ');
Min18= input ('Input Minimum Utilisation CRN18 = ');
Max18= input ('Input Maximum Utilisation CRN18 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
ScalabilityCRN10 = input('Input the Scalability of CRN10 = ');
ScalabilityCRN11 = input('Input the Scalability of CRN11 = ');
ScalabilityCRN12 = input('Input the Scalability of CRN12 = ');
ScalabilityCRN13 = input('Input the Scalability of CRN13 = ');
ScalabilityCRN14 = input('Input the Scalability of CRN14 = ');
ScalabilityCRN15 = input('Input the Scalability of CRN15 = ');
ScalabilityCRN16 = input('Input the Scalability of CRN16 = ');
ScalabilityCRN17 = input('Input the Scalability of CRN17 = ');
ScalabilityCRN18 = input('Input the Scalability of CRN18 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9 +
ScalabilityCRN10 + ScalabilityCRN11 + ScalabilityCRN12 +
ScalabilityCRN13 + ScalabilityCRN14 + ScalabilityCRN15 +
ScalabilityCRN16 + ScalabilityCRN17 + ScalabilityCRN18;
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==19)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
Min9= input ('Input Minimum Utilisation CRN9 = ');
Max9= input ('Input Maximum Utilisation CRN9 = ');
Min10= input ('Input Minimum Utilisation CRN10 = ');
Max10= input ('Input Maximum Utilisation CRN10 = ');
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Min11= input ('Input Minimum Utilisation CRN11 = ');
Max11= input ('Input Maximum Utilisation CRN11 = ');
Min12= input ('Input Minimum Utilisation CRN12 = ');
Max12= input ('Input Maximum Utilisation CRN12 = ');
Min13= input ('Input Minimum Utilisation CRN13 = ');
Max13= input ('Input Maximum Utilisation CRN13 = ');
Min14= input ('Input Minimum Utilisation CRN14 = ');
Max14= input ('Input Maximum Utilisation CRN14 = ');
Min15= input ('Input Minimum Utilisation CRN15 = ');
Max15= input ('Input Maximum Utilisation CRN15 = ');
Min16= input ('Input Minimum Utilisation CRN16 = ');
Max16= input ('Input Maximum Utilisation CRN16 = ');
Min17= input ('Input Minimum Utilisation CRN17 = ');
Max17= input ('Input Maximum Utilisation CRN17 = ');
Min18= input ('Input Minimum Utilisation CRN18 = ');
Max18= input ('Input Maximum Utilisation CRN18 = ');
Min19= input ('Input Minimum Utilisation CRN19 = ');
Max19= input ('Input Maximum Utilisation CRN19 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
ScalabilityCRN10 = input('Input the Scalability of CRN10 = ');
ScalabilityCRN11 = input('Input the Scalability of CRN11 = ');
ScalabilityCRN12 = input('Input the Scalability of CRN12 = ');
ScalabilityCRN13 = input('Input the Scalability of CRN13 = ');
ScalabilityCRN14 = input('Input the Scalability of CRN14 = ');
ScalabilityCRN15 = input('Input the Scalability of CRN15 = ');
ScalabilityCRN16 = input('Input the Scalability of CRN16 = ');
ScalabilityCRN17 = input('Input the Scalability of CRN17 = ');
ScalabilityCRN18 = input('Input the Scalability of CRN18 = ');
ScalabilityCRN19 = input('Input the Scalability of CRN19 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9 +
ScalabilityCRN10 + ScalabilityCRN11 + ScalabilityCRN12 +
ScalabilityCRN13 + ScalabilityCRN14 + ScalabilityCRN15 +
ScalabilityCRN16 + ScalabilityCRN17 + ScalabilityCRN18 +
ScalabilityCRN19;
guardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
if (N==20)
Min1= input ('Input Minimum Utilisation CRN1 = ');
Max1= input ('Input Maximum Utilisation CRN1 = ');
Min2= input ('Input Minimum Utilisation CRN2 = ');
Max2= input ('Input Maximum Utilisation CRN2 = ');
Min3= input ('Input Minimum Utilisation CRN3 = ');
Max3= input ('Input Maximum Utilisation CRN3 = ');
Min4= input ('Input Minimum Utilisation CRN4 = ');
Max4= input ('Input Maximum Utilisation CRN4 = ');
Min5= input ('Input Minimum Utilisation CRN5 = ');
Max5= input ('Input Maximum Utilisation CRN5 = ');
Min6= input ('Input Minimum Utilisation CRN6 = ');
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Max6= input ('Input Maximum Utilisation CRN6 = ');
Min7= input ('Input Minimum Utilisation CRN7 = ');
Max7= input ('Input Maximum Utilisation CRN7 = ');
Min8= input ('Input Minimum Utilisation CRN8 = ');
Max8= input ('Input Maximum Utilisation CRN8 = ');
Min9= input ('Input Minimum Utilisation CRN9 = ');
Max9= input ('Input Maximum Utilisation CRN9 = ');
Min10= input ('Input Minimum Utilisation CRN10 = ');
Max10= input ('Input Maximum Utilisation CRN10 = ');
Min11= input ('Input Minimum Utilisation CRN11 = ');
Max11= input ('Input Maximum Utilisation CRN11 = ');
Min12= input ('Input Minimum Utilisation CRN12 = ');
Max12= input ('Input Maximum Utilisation CRN12 = ');
Min13= input ('Input Minimum Utilisation CRN13 = ');
Max13= input ('Input Maximum Utilisation CRN13 = ');
Min14= input ('Input Minimum Utilisation CRN14 = ');
Max14= input ('Input Maximum Utilisation CRN14 = ');
Min15= input ('Input Minimum Utilisation CRN15 = ');
Max15= input ('Input Maximum Utilisation CRN15 = ');
Min16= input ('Input Minimum Utilisation CRN16 = ');
Max16= input ('Input Maximum Utilisation CRN16 = ');
Min17= input ('Input Minimum Utilisation CRN17 = ');
Max17= input ('Input Maximum Utilisation CRN17 = ');
Min18= input ('Input Minimum Utilisation CRN18 = ');
Max18= input ('Input Maximum Utilisation CRN18 = ');
Min19= input ('Input Minimum Utilisation CRN19 = ');
Max19= input ('Input Maximum Utilisation CRN19 = ');
Min20= input ('Input Minimum Utilisation CRN20 = ');
Max20= input ('Input Maximum Utilisation CRN20 = ');
ScalabilityCRN1 = input('Input the Scalability of CRN1 = ');
ScalabilityCRN2 = input('Input the Scalability of CRN2 = ');
ScalabilityCRN3 = input('Input the Scalability of CRN3 = ');
ScalabilityCRN4 = input('Input the Scalability of CRN4 = ');
ScalabilityCRN5 = input('Input the Scalability of CRN5 = ');
ScalabilityCRN6 = input('Input the Scalability of CRN6 = ');
ScalabilityCRN7 = input('Input the Scalability of CRN7 = ');
ScalabilityCRN8 = input('Input the Scalability of CRN8 = ');
ScalabilityCRN9 = input('Input the Scalability of CRN9 = ');
ScalabilityCRN10 = input('Input the Scalability of CRN10 = ');
ScalabilityCRN11 = input('Input the Scalability of CRN11 = ');
ScalabilityCRN12 = input('Input the Scalability of CRN12 = ');
ScalabilityCRN13 = input('Input the Scalability of CRN13 = ');
ScalabilityCRN14 = input('Input the Scalability of CRN14 = ');
ScalabilityCRN15 = input('Input the Scalability of CRN15 = ');
ScalabilityCRN16 = input('Input the Scalability of CRN16 = ');
ScalabilityCRN17 = input('Input the Scalability of CRN17 = ');
ScalabilityCRN18 = input('Input the Scalability of CRN18 = ');
ScalabilityCRN19 = input('Input the Scalability of CRN19 = ');
ScalabilityCRN20 = input('Input the Scalability of CRN20 = ');
ScalabilityTOT = ScalabilityCRN1 + ScalabilityCRN2 +
ScalabilityCRN3 + ScalabilityCRN4 + ScalabilityCRN5 + ScalabilityCRN6
+ ScalabilityCRN7 + ScalabilityCRN8 + ScalabilityCRN9 +
ScalabilityCRN10 + ScalabilityCRN11 + ScalabilityCRN12 +
ScalabilityCRN13 + ScalabilityCRN14 + ScalabilityCRN15 +
ScalabilityCRN16 + ScalabilityCRN17 + ScalabilityCRN18 +
ScalabilityCRN19 + ScalabilityCRN20;
gardspectrum = input ('Input Guard Spectrum to Avoid Saturated
Case = ');
DeltaOccpancy = input ('Input Expected Promotion in Spectrum
Utilising of Primary Networks = ');
end
```

```
for It=1:1:Iterations
    disp ('the iteration number=')
    disp (It)
    Tavch = 0;
    AvTavch = 0;
    N = Toset;
    SpectAvailable = 0;
    Specttests = MinimumAvailableSpectrum + (rand
(1,Tests)*(MaximumAvailableSpectrum-MinimumAvailableSpectrum));
    Specttestsav = mean(Specttests);
    disp ('Average Available Spectrum is');
    disp (Specttestsav);
    if (N==1)
        Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
        avchnet(1) = mean (Net1);
        MX(1) = max(Net1);
        MI(1) = min(Net1);
        %Tavch = avchnet(1);
        AvTavch = max (avchnet);
    end
    if (N==2)
        Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
        Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
        avchnet(1) = mean (Net1);
        avchnet(2) = mean (Net2);
        MX(1) = max(Net1);
        MI(1) = min(Net1);
        MX(2) = max(Net2);
        MI(2) = min(Net2);
        %Tavch = avchnet(1) + avchnet(2);
        AvTavch = max (avchnet);
    end
    if (N==3)
        Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
        Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
        Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
        avchnet(1) = mean (Net1);
        avchnet(2) = mean (Net2);
        avchnet(3) = mean (Net3);
        MX(1) = max(Net1);
        MI(1) = min(Net1);
        MX(2) = max(Net2);
        MI(2) = min(Net2);
        MX(3) = max(Net3);
        MI(3) = min(Net3);
        %Tavch = avchnet(1) + avchnet(2) + avchnet(3);
        AvTavch = max (avchnet);
    end
    if (N==4)
        Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
        Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
        Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
        Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
        avchnet(1) = mean (Net1);
        avchnet(2) = mean (Net2);
        avchnet(3) = mean (Net3);
        avchnet(4) = mean (Net4);
        MX(1) = max(Net1);
        MI(1) = min(Net1);
        MX(2) = max(Net2);
        MI(2) = min(Net2);
```

```
MX(3) = max(Net3);
MI(3) = min(Net3);
MX(4) = max(Net4);
MI(4) = min(Net4);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4);
AvTavch = max (avchnet);
end
if (N==5)
    Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
    Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
    Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
    Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
    Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
    avchnet(1) = mean (Net1);
    avchnet(2) = mean (Net2);
    avchnet(3) = mean (Net3);
    avchnet(4) = mean (Net4);
    avchnet(5) = mean (Net5);
    MX(1) = max(Net1);
    MI(1) = min(Net1);
    MX(2) = max(Net2);
    MI(2) = min(Net2);
    MX(3) = max(Net3);
    MI(3) = min(Net3);
    MX(4) = max(Net4);
    MI(4) = min(Net4);
    MX(5) = max(Net5);
    MI(5) = min(Net5);
    %Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5);
    AvTavch = max (avchnet);
end
if (N==6)
    Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
    Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
    Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
    Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
    Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
    Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
    avchnet(1) = mean (Net1);
    avchnet(2) = mean (Net2);
    avchnet(3) = mean (Net3);
    avchnet(4) = mean (Net4);
    avchnet(5) = mean (Net5);
    avchnet(6) = mean (Net6);
    MX(1) = max(Net1);
    MI(1) = min(Net1);
    MX(2) = max(Net2);
    MI(2) = min(Net2);
    MX(3) = max(Net3);
    MI(3) = min(Net3);
    MX(4) = max(Net4);
    MI(4) = min(Net4);
    MX(5) = max(Net5);
    MI(5) = min(Net5);
    MX(6) = max(Net6);
    MI(6) = min(Net6);
    %Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6);
    AvTavch = max (avchnet);
end
```

```
if (N==7)
    Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
    Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
    Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
    Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
    Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
    Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
    Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
    avchnet(1) = mean (Net1);
    avchnet(2) = mean (Net2);
    avchnet(3) = mean (Net3);
    avchnet(4) = mean (Net4);
    avchnet(5) = mean (Net5);
    avchnet(6) = mean (Net6);
    avchnet(7) = mean (Net7);
    MX(1) = max(Net1);
    MI(1) = min(Net1);
    MX(2) = max(Net2);
    MI(2) = min(Net2);
    MX(3) = max(Net3);
    MI(3) = min(Net3);
    MX(4) = max(Net4);
    MI(4) = min(Net4);
    MX(5) = max(Net5);
    MI(5) = min(Net5);
    MX(6) = max(Net6);
    MI(6) = min(Net6);
    MX(7) = max(Net7);
    MI(7) = min(Net7);
    %Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7);
    AvTavch = max (avchnet);
end
if (N==8)
    Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
    Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
    Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
    Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
    Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
    Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
    Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
    Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
    avchnet(1) = mean (Net1);
    avchnet(2) = mean (Net2);
    avchnet(3) = mean (Net3);
    avchnet(4) = mean (Net4);
    avchnet(5) = mean (Net5);
    avchnet(6) = mean (Net6);
    avchnet(7) = mean (Net7);
    avchnet(8) = mean (Net8);
    MX(1) = max(Net1);
    MI(1) = min(Net1);
    MX(2) = max(Net2);
    MI(2) = min(Net2);
    MX(3) = max(Net3);
    MI(3) = min(Net3);
    MX(4) = max(Net4);
    MI(4) = min(Net4);
    MX(5) = max(Net5);
    MI(5) = min(Net5);
    MX(6) = max(Net6);
```

```
MI(6) = min(Net6);
MX(7) = max(Net7);
MI(7) = min(Net7);
MX(8) = max(Net8);
MI(8) = min(Net8);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8);
AvTavch = max (avchnet);
end
if (N==9)
    Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
    Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
    Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
    Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
    Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
    Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
    Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
    Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
    Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
    avchnet(1) = mean (Net1);
    avchnet(2) = mean (Net2);
    avchnet(3) = mean (Net3);
    avchnet(4) = mean (Net4);
    avchnet(5) = mean (Net5);
    avchnet(6) = mean (Net6);
    avchnet(7) = mean (Net7);
    avchnet(8) = mean (Net8);
    avchnet(9) = mean (Net9);
    MX(1) = max(Net1);
    MI(1) = min(Net1);
    MX(2) = max(Net2);
    MI(2) = min(Net2);
    MX(3) = max(Net3);
    MI(3) = min(Net3);
    MX(4) = max(Net4);
    MI(4) = min(Net4);
    MX(5) = max(Net5);
    MI(5) = min(Net5);
    MX(6) = max(Net6);
    MI(6) = min(Net6);
    MX(7) = max(Net7);
    MI(7) = min(Net7);
    MX(8) = max(Net8);
    MI(8) = min(Net8);
    MX(9) = max(Net9);
    MI(9) = min(Net9);
    %Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9);
    AvTavch = max (avchnet);
end
if (N==10)
    Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
    Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
    Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
    Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
    Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
    Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
    Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
    Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
    Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
    Net10 = Min10 + (rand (1,Tests)*(Max10-Min10));
```

```
avchnet(1) = mean (Net1);
avchnet(2) = mean (Net2);
avchnet(3) = mean (Net3);
avchnet(4) = mean (Net4);
avchnet(5) = mean (Net5);
avchnet(6) = mean (Net6);
avchnet(7) = mean (Net7);
avchnet(8) = mean (Net8);
avchnet(9) = mean (Net9);
avchnet(10) = mean (Net10);
MX(1) = max(Net1);
MI(1) = min(Net1);
MX(2) = max(Net2);
MI(2) = min(Net2);
MX(3) = max(Net3);
MI(3) = min(Net3);
MX(4) = max(Net4);
MI(4) = min(Net4);
MX(5) = max(Net5);
MI(5) = min(Net5);
MX(6) = max(Net6);
MI(6) = min(Net6);
MX(7) = max(Net7);
MI(7) = min(Net7);
MX(8) = max(Net8);
MI(8) = min(Net8);
MX(9) = max(Net9);
MI(9) = min(Net9);
MX(10) = max(Net10);
MI(10) = min(Net10);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9) +
avchnet(10);
AvTavch = max (avchnet);
end
if (N==11)
Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
Net10 = Min10 + (rand (1,Tests)*(Max10-Min10));
Net11 = Min11 + (rand (1,Tests)*(Max11-Min11));
avchnet(1) = mean (Net1);
avchnet(2) = mean (Net2);
avchnet(3) = mean (Net3);
avchnet(4) = mean (Net4);
avchnet(5) = mean (Net5);
avchnet(6) = mean (Net6);
avchnet(7) = mean (Net7);
avchnet(8) = mean (Net8);
avchnet(9) = mean (Net9);
avchnet(10) = mean (Net10);
avchnet(11) = mean (Net11);
MX(1) = max(Net1);
MI(1) = min(Net1);
MX(2) = max(Net2);
```

```
MI(2) = min(Net2);
MX(3) = max(Net3);
MI(3) = min(Net3);
MX(4) = max(Net4);
MI(4) = min(Net4);
MX(5) = max(Net5);
MI(5) = min(Net5);
MX(6) = max(Net6);
MI(6) = min(Net6);
MX(7) = max(Net7);
MI(7) = min(Net7);
MX(8) = max(Net8);
MI(8) = min(Net8);
MX(9) = max(Net9);
MI(9) = min(Net9);
MX(10) = max(Net10);
MI(10) = min(Net10);
MX(11) = max(Net11);
MI(11) = min(Net11);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9) +
avchnet(10) + avchnet(11);
AvTavch = max (avchnet);
end
if (N==12)
Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
Net10 = Min10 + (rand (1,Tests)*(Max10-Min10));
Net11 = Min11 + (rand (1,Tests)*(Max11-Min11));
Net12 = Min12 + (rand (1,Tests)*(Max12-Min12));
avchnet(1) = mean (Net1);
avchnet(2) = mean (Net2);
avchnet(3) = mean (Net3);
avchnet(4) = mean (Net4);
avchnet(5) = mean (Net5);
avchnet(6) = mean (Net6);
avchnet(7) = mean (Net7);
avchnet(8) = mean (Net8);
avchnet(9) = mean (Net9);
avchnet(10) = mean (Net10);
avchnet(11) = mean (Net11);
avchnet(12) = mean (Net12);
MX(1) = max(Net1);
MI(1) = min(Net1);
MX(2) = max(Net2);
MI(2) = min(Net2);
MX(3) = max(Net3);
MI(3) = min(Net3);
MX(4) = max(Net4);
MI(4) = min(Net4);
MX(5) = max(Net5);
MI(5) = min(Net5);
MX(6) = max(Net6);
MI(6) = min(Net6);
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```
MX(7) = max(Net7);
MI(7) = min(Net7);
MX(8) = max(Net8);
MI(8) = min(Net8);
MX(9) = max(Net9);
MI(9) = min(Net9);
MX(10) = max(Net10);
MI(10) = min(Net10);
MX(11) = max(Net11);
MI(11) = min(Net11);
MX(12) = max(Net12);
MI(12) = min(Net12);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9) +
avchnet(10) + avchnet(11) + avchnet(12);
AvTavch = max (avchnet);
end
if (N==13)
Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
Net10 = Min10 + (rand (1,Tests)*(Max10-Min10));
Net11 = Min11 + (rand (1,Tests)*(Max11-Min11));
Net12 = Min12 + (rand (1,Tests)*(Max12-Min12));
Net13 = Min13 + (rand (1,Tests)*(Max13-Min13));
avchnet(1) = mean (Net1);
avchnet(2) = mean (Net2);
avchnet(3) = mean (Net3);
avchnet(4) = mean (Net4);
avchnet(5) = mean (Net5);
avchnet(6) = mean (Net6);
avchnet(7) = mean (Net7);
avchnet(8) = mean (Net8);
avchnet(9) = mean (Net9);
avchnet(10) = mean (Net10);
avchnet(11) = mean (Net11);
avchnet(12) = mean (Net12);
avchnet(13) = mean (Net13);
MX(1) = max(Net1);
MI(1) = min(Net1);
MX(2) = max(Net2);
MI(2) = min(Net2);
MX(3) = max(Net3);
MI(3) = min(Net3);
MX(4) = max(Net4);
MI(4) = min(Net4);
MX(5) = max(Net5);
MI(5) = min(Net5);
MX(6) = max(Net6);
MI(6) = min(Net6);
MX(7) = max(Net7);
MI(7) = min(Net7);
MX(8) = max(Net8);
MI(8) = min(Net8);
MX(9) = max(Net9);
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MI(9) = min(Net9);
MX(10) = max(Net10);
MI(10) = min(Net10);
MX(11) = max(Net11);
MI(11) = min(Net11);
MX(12) = max(Net12);
MI(12) = min(Net12);
MX(13) = max(Net13);
MI(13) = min(Net13);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9) +
avchnet(10) + avchnet(11) + avchnet(12) + avchnet(13);
AvTavch = max (avchnet);
end
if (N==14)
Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
Net10 = Min10 + (rand (1,Tests)*(Max10-Min10));
Net11 = Min11 + (rand (1,Tests)*(Max11-Min11));
Net12 = Min12 + (rand (1,Tests)*(Max12-Min12));
Net13 = Min13 + (rand (1,Tests)*(Max13-Min13));
Net14 = Min14 + (rand (1,Tests)*(Max14-Min14));
avchnet(1) = mean (Net1);
avchnet(2) = mean (Net2);
avchnet(3) = mean (Net3);
avchnet(4) = mean (Net4);
avchnet(5) = mean (Net5);
avchnet(6) = mean (Net6);
avchnet(7) = mean (Net7);
avchnet(8) = mean (Net8);
avchnet(9) = mean (Net9);
avchnet(10) = mean (Net10);
avchnet(11) = mean (Net11);
avchnet(12) = mean (Net12);
avchnet(13) = mean (Net13);
avchnet(14) = mean (Net14);
MX(1) = max(Net1);
MI(1) = min(Net1);
MX(2) = max(Net2);
MI(2) = min(Net2);
MX(3) = max(Net3);
MI(3) = min(Net3);
MX(4) = max(Net4);
MI(4) = min(Net4);
MX(5) = max(Net5);
MI(5) = min(Net5);
MX(6) = max(Net6);
MI(6) = min(Net6);
MX(7) = max(Net7);
MI(7) = min(Net7);
MX(8) = max(Net8);
MI(8) = min(Net8);
MX(9) = max(Net9);
MI(9) = min(Net9);
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MX(10) = max(Net10);
MI(10) = min(Net10);
MX(11) = max(Net11);
MI(11) = min(Net11);
MX(12) = max(Net12);
MI(12) = min(Net12);
MX(13) = max(Net13);
MI(13) = min(Net13);
MX(14) = max(Net14);
MI(14) = min(Net14);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9) +
avchnet(10) + avchnet(11) + avchnet(12) + avchnet(13) + avchnet(14);
AvTavch = max (avchnet);
end
if (N==15)
Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
Net10 = Min10 + (rand (1,Tests)*(Max10-Min10));
Net11 = Min11 + (rand (1,Tests)*(Max11-Min11));
Net12 = Min12 + (rand (1,Tests)*(Max12-Min12));
Net13 = Min13 + (rand (1,Tests)*(Max13-Min13));
Net14 = Min14 + (rand (1,Tests)*(Max14-Min14));
Net15 = Min15 + (rand (1,Tests)*(Max15-Min15));
avchnet(1) = mean (Net1);
avchnet(2) = mean (Net2);
avchnet(3) = mean (Net3);
avchnet(4) = mean (Net4);
avchnet(5) = mean (Net5);
avchnet(6) = mean (Net6);
avchnet(7) = mean (Net7);
avchnet(8) = mean (Net8);
avchnet(9) = mean (Net9);
avchnet(10) = mean (Net10);
avchnet(11) = mean (Net11);
avchnet(12) = mean (Net12);
avchnet(13) = mean (Net13);
avchnet(14) = mean (Net14);
avchnet(15) = mean (Net15);
MX(1) = max(Net1);
MI(1) = min(Net1);
MX(2) = max(Net2);
MI(2) = min(Net2);
MX(3) = max(Net3);
MI(3) = min(Net3);
MX(4) = max(Net4);
MI(4) = min(Net4);
MX(5) = max(Net5);
MI(5) = min(Net5);
MX(6) = max(Net6);
MI(6) = min(Net6);
MX(7) = max(Net7);
MI(7) = min(Net7);
MX(8) = max(Net8);
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```
MI(8) = min(Net8);
MX(9) = max(Net9);
MI(9) = min(Net9);
MX(10) = max(Net10);
MI(10) = min(Net10);
MX(11) = max(Net11);
MI(11) = min(Net11);
MX(12) = max(Net12);
MI(12) = min(Net12);
MX(13) = max(Net13);
MI(13) = min(Net13);
MX(14) = max(Net14);
MI(14) = min(Net14);
MX(15) = max(Net15);
MI(15) = min(Net15);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9) +
avchnet(10) + avchnet(11) + avchnet(12) + avchnet(13) + avchnet(14) +
avchnet(15);
AvTavch = max (avchnet);
end
if (N==16)
Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
Net10 = Min10 + (rand (1,Tests)*(Max10-Min10));
Net11 = Min11 + (rand (1,Tests)*(Max11-Min11));
Net12 = Min12 + (rand (1,Tests)*(Max12-Min12));
Net13 = Min13 + (rand (1,Tests)*(Max13-Min13));
Net14 = Min14 + (rand (1,Tests)*(Max14-Min14));
Net15 = Min15 + (rand (1,Tests)*(Max15-Min15));
Net16 = Min16 + (rand (1,Tests)*(Max16-Min16));
avchnet(1) = mean (Net1);
avchnet(2) = mean (Net2);
avchnet(3) = mean (Net3);
avchnet(4) = mean (Net4);
avchnet(5) = mean (Net5);
avchnet(6) = mean (Net6);
avchnet(7) = mean (Net7);
avchnet(8) = mean (Net8);
avchnet(9) = mean (Net9);
avchnet(10) = mean (Net10);
avchnet(11) = mean (Net11);
avchnet(12) = mean (Net12);
avchnet(13) = mean (Net13);
avchnet(14) = mean (Net14);
avchnet(15) = mean (Net15);
avchnet(16) = mean (Net16);
MX(1) = max(Net1);
MI(1) = min(Net1);
MX(2) = max(Net2);
MI(2) = min(Net2);
MX(3) = max(Net3);
MI(3) = min(Net3);
MX(4) = max(Net4);
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```
MI(4) = min(Net4);
MX(5) = max(Net5);
MI(5) = min(Net5);
MX(6) = max(Net6);
MI(6) = min(Net6);
MX(7) = max(Net7);
MI(7) = min(Net7);
MX(8) = max(Net8);
MI(8) = min(Net8);
MX(9) = max(Net9);
MI(9) = min(Net9);
MX(10) = max(Net10);
MI(10) = min(Net10);
MX(11) = max(Net11);
MI(11) = min(Net11);
MX(12) = max(Net12);
MI(12) = min(Net12);
MX(13) = max(Net13);
MI(13) = min(Net13);
MX(14) = max(Net14);
MI(14) = min(Net14);
MX(15) = max(Net15);
MI(15) = min(Net15);
MX(16) = max(Net16);
MI(16) = min(Net16);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9) +
avchnet(10) + avchnet(11) + avchnet(12) + avchnet(13) + avchnet(14) +
avchnet(15) + avchnet(16);
AvTavch = max (avchnet);
end
if (N==17)
Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
Net10 = Min10 + (rand (1,Tests)*(Max10-Min10));
Net11 = Min11 + (rand (1,Tests)*(Max11-Min11));
Net12 = Min12 + (rand (1,Tests)*(Max12-Min12));
Net13 = Min13 + (rand (1,Tests)*(Max13-Min13));
Net14 = Min14 + (rand (1,Tests)*(Max14-Min14));
Net15 = Min15 + (rand (1,Tests)*(Max15-Min15));
Net16 = Min16 + (rand (1,Tests)*(Max16-Min16));
Net17 = Min17 + (rand (1,Tests)*(Max17-Min17));
avchnet(1) = mean (Net1);
avchnet(2) = mean (Net2);
avchnet(3) = mean (Net3);
avchnet(4) = mean (Net4);
avchnet(5) = mean (Net5);
avchnet(6) = mean (Net6);
avchnet(7) = mean (Net7);
avchnet(8) = mean (Net8);
avchnet(9) = mean (Net9);
avchnet(10) = mean (Net10);
avchnet(11) = mean (Net11);
avchnet(12) = mean (Net12);
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avchnet(13) = mean (Net13);
avchnet(14) = mean (Net14);
avchnet(15) = mean (Net15);
avchnet(16) = mean (Net16);
MX(1) = max(Net1);
MI(1) = min(Net1);
MX(2) = max(Net2);
MI(2) = min(Net2);
MX(3) = max(Net3);
MI(3) = min(Net3);
MX(4) = max(Net4);
MI(4) = min(Net4);
MX(5) = max(Net5);
MI(5) = min(Net5);
MX(6) = max(Net6);
MI(6) = min(Net6);
MX(7) = max(Net7);
MI(7) = min(Net7);
MX(8) = max(Net8);
MI(8) = min(Net8);
MX(9) = max(Net9);
MI(9) = min(Net9);
MX(10) = max(Net10);
MI(10) = min(Net10);
MX(11) = max(Net11);
MI(11) = min(Net11);
MX(12) = max(Net12);
MI(12) = min(Net12);
MX(13) = max(Net13);
MI(13) = min(Net13);
MX(14) = max(Net14);
MI(14) = min(Net14);
MX(15) = max(Net15);
MI(15) = min(Net15);
MX(16) = max(Net16);
MI(16) = min(Net16);
MX(17) = max(Net17);
MI(17) = min(Net17);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9) +
avchnet(10) + avchnet(11) + avchnet(12) + avchnet(13) + avchnet(14) +
avchnet(15) + avchnet(16) + avchnet(17);
AvTavch = max (avchnet);
end
if (N==18)
Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
Net10 = Min10 + (rand (1,Tests)*(Max10-Min10));
Net11 = Min11 + (rand (1,Tests)*(Max11-Min11));
Net12 = Min12 + (rand (1,Tests)*(Max12-Min12));
Net13 = Min13 + (rand (1,Tests)*(Max13-Min13));
Net14 = Min14 + (rand (1,Tests)*(Max14-Min14));
Net15 = Min15 + (rand (1,Tests)*(Max15-Min15));
Net16 = Min16 + (rand (1,Tests)*(Max16-Min16));
```

```
Net17 = Min17 + (rand (1,Tests)*(Max17-Min17));
Net18 = Min18 + (rand (1,Tests)*(Max18-Min18));
avchnet(1) = mean (Net1);
avchnet(2) = mean (Net2);
avchnet(3) = mean (Net3);
avchnet(4) = mean (Net4);
avchnet(5) = mean (Net5);
avchnet(6) = mean (Net6);
avchnet(7) = mean (Net7);
avchnet(8) = mean (Net8);
avchnet(9) = mean (Net9);
avchnet(10) = mean (Net10);
avchnet(11) = mean (Net11);
avchnet(12) = mean (Net12);
avchnet(13) = mean (Net13);
avchnet(14) = mean (Net14);
avchnet(15) = mean (Net15);
avchnet(16) = mean (Net16);
avchnet(17) = mean (Net17);
avchnet(18) = mean (Net18);
MX(1) = max(Net1);
MI(1) = min(Net1);
MX(2) = max(Net2);
MI(2) = min(Net2);
MX(3) = max(Net3);
MI(3) = min(Net3);
MX(4) = max(Net4);
MI(4) = min(Net4);
MX(5) = max(Net5);
MI(5) = min(Net5);
MX(6) = max(Net6);
MI(6) = min(Net6);
MX(7) = max(Net7);
MI(7) = min(Net7);
MX(8) = max(Net8);
MI(8) = min(Net8);
MX(9) = max(Net9);
MI(9) = min(Net9);
MX(10) = max(Net10);
MI(10) = min(Net10);
MX(11) = max(Net11);
MI(11) = min(Net11);
MX(12) = max(Net12);
MI(12) = min(Net12);
MX(13) = max(Net13);
MI(13) = min(Net13);
MX(14) = max(Net14);
MI(14) = min(Net14);
MX(15) = max(Net15);
MI(15) = min(Net15);
MX(16) = max(Net16);
MI(16) = min(Net16);
MX(17) = max(Net17);
MI(17) = min(Net17);
MX(18) = max(Net18);
MI(18) = min(Net18);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9) +
avchnet(10) + avchnet(11) + avchnet(12) + avchnet(13) + avchnet(14) +
avchnet(15) + avchnet(16) + avchnet(17) + avchnet(18);
AvTavch = max (avchnet);
```

```
end
if (N==19)
    Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
    Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
    Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
    Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
    Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
    Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
    Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
    Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
    Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
    Net10 = Min10 + (rand (1,Tests)*(Max10-Min10));
    Net11 = Min11 + (rand (1,Tests)*(Max11-Min11));
    Net12 = Min12 + (rand (1,Tests)*(Max12-Min12));
    Net13 = Min13 + (rand (1,Tests)*(Max13-Min13));
    Net14 = Min14 + (rand (1,Tests)*(Max14-Min14));
    Net15 = Min15 + (rand (1,Tests)*(Max15-Min15));
    Net16 = Min16 + (rand (1,Tests)*(Max16-Min16));
    Net17 = Min17 + (rand (1,Tests)*(Max17-Min17));
    Net18 = Min18 + (rand (1,Tests)*(Max18-Min18));
    Net19 = Min19 + (rand (1,Tests)*(Max19-Min19));
    avchnet(1) = mean (Net1);
    avchnet(2) = mean (Net2);
    avchnet(3) = mean (Net3);
    avchnet(4) = mean (Net4);
    avchnet(5) = mean (Net5);
    avchnet(6) = mean (Net6);
    avchnet(7) = mean (Net7);
    avchnet(8) = mean (Net8);
    avchnet(9) = mean (Net9);
    avchnet(10) = mean (Net10);
    avchnet(11) = mean (Net11);
    avchnet(12) = mean (Net12);
    avchnet(13) = mean (Net13);
    avchnet(14) = mean (Net14);
    avchnet(15) = mean (Net15);
    avchnet(16) = mean (Net16);
    avchnet(17) = mean (Net17);
    avchnet(18) = mean (Net18);
    avchnet(19) = mean (Net19);
    MX(1) = max(Net1);
    MI(1) = min(Net1);
    MX(2) = max(Net2);
    MI(2) = min(Net2);
    MX(3) = max(Net3);
    MI(3) = min(Net3);
    MX(4) = max(Net4);
    MI(4) = min(Net4);
    MX(5) = max(Net5);
    MI(5) = min(Net5);
    MX(6) = max(Net6);
    MI(6) = min(Net6);
    MX(7) = max(Net7);
    MI(7) = min(Net7);
    MX(8) = max(Net8);
    MI(8) = min(Net8);
    MX(9) = max(Net9);
    MI(9) = min(Net9);
    MX(10) = max(Net10);
    MI(10) = min(Net10);
    MX(11) = max(Net11);
```

```
MI(11) = min(Net11);
MX(12) = max(Net12);
MI(12) = min(Net12);
MX(13) = max(Net13);
MI(13) = min(Net13);
MX(14) = max(Net14);
MI(14) = min(Net14);
MX(15) = max(Net15);
MI(15) = min(Net15);
MX(16) = max(Net16);
MI(16) = min(Net16);
MX(17) = max(Net17);
MI(17) = min(Net17);
MX(18) = max(Net18);
MI(18) = min(Net18);
MX(19) = max(Net19);
MI(19) = min(Net19);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9) +
avchnet(10) + avchnet(11) + avchnet(12) + avchnet(13) + avchnet(14) +
avchnet(15) + avchnet(16) + avchnet(17) + avchnet(18) + avchnet(19);
AvTavch = max (avchnet);
end
if (N==20)
    Net1 = Min1 + (rand (1,Tests)*(Max1-Min1));
    Net2 = Min2 + (rand (1,Tests)*(Max2-Min2));
    Net3 = Min3 + (rand (1,Tests)*(Max3-Min3));
    Net4 = Min4 + (rand (1,Tests)*(Max4-Min4));
    Net5 = Min5 + (rand (1,Tests)*(Max5-Min5));
    Net6 = Min6 + (rand (1,Tests)*(Max6-Min6));
    Net7 = Min7 + (rand (1,Tests)*(Max7-Min7));
    Net8 = Min8 + (rand (1,Tests)*(Max8-Min8));
    Net9 = Min9 + (rand (1,Tests)*(Max9-Min9));
    Net10 = Min10 + (rand (1,Tests)*(Max10-Min10));
    Net11 = Min11 + (rand (1,Tests)*(Max11-Min11));
    Net12 = Min12 + (rand (1,Tests)*(Max12-Min12));
    Net13 = Min13 + (rand (1,Tests)*(Max13-Min13));
    Net14 = Min14 + (rand (1,Tests)*(Max14-Min14));
    Net15 = Min15 + (rand (1,Tests)*(Max15-Min15));
    Net16 = Min16 + (rand (1,Tests)*(Max16-Min16));
    Net17 = Min17 + (rand (1,Tests)*(Max17-Min17));
    Net18 = Min18 + (rand (1,Tests)*(Max18-Min18));
    Net19 = Min19 + (rand (1,Tests)*(Max19-Min19));
    Net20 = Min20 + (rand (1,Tests)*(Max20-Min20));
    avchnet(1) = mean (Net1);
    avchnet(2) = mean (Net2);
    avchnet(3) = mean (Net3);
    avchnet(4) = mean (Net4);
    avchnet(5) = mean (Net5);
    avchnet(6) = mean (Net6);
    avchnet(7) = mean (Net7);
    avchnet(8) = mean (Net8);
    avchnet(9) = mean (Net9);
    avchnet(10) = mean (Net10);
    avchnet(11) = mean (Net11);
    avchnet(12) = mean (Net12);
    avchnet(13) = mean (Net13);
    avchnet(14) = mean (Net14);
    avchnet(15) = mean (Net15);
    avchnet(16) = mean (Net16);
    avchnet(17) = mean (Net17);
```



```
avchnet(18) = mean (Net18);
avchnet(19) = mean (Net19);
avchnet(20) = mean (Net20);
MX(1) = max(Net1);
MI(1) = min(Net1);
MX(2) = max(Net2);
MI(2) = min(Net2);
MX(3) = max(Net3);
MI(3) = min(Net3);
MX(4) = max(Net4);
MI(4) = min(Net4);
MX(5) = max(Net5);
MI(5) = min(Net5);
MX(6) = max(Net6);
MI(6) = min(Net6);
MX(7) = max(Net7);
MI(7) = min(Net7);
MX(8) = max(Net8);
MI(8) = min(Net8);
MX(9) = max(Net9);
MI(9) = min(Net9);
MX(10) = max(Net10);
MI(10) = min(Net10);
MX(11) = max(Net11);
MI(11) = min(Net11);
MX(12) = max(Net12);
MI(12) = min(Net12);
MX(13) = max(Net13);
MI(13) = min(Net13);
MX(14) = max(Net14);
MI(14) = min(Net14);
MX(15) = max(Net15);
MI(15) = min(Net15);
MX(16) = max(Net16);
MI(16) = min(Net16);
MX(17) = max(Net17);
MI(17) = min(Net17);
MX(18) = max(Net18);
MI(18) = min(Net18);
MX(19) = max(Net19);
MI(19) = min(Net19);
MX(20) = max(Net20);
MI(20) = min(Net20);
%Tavch = avchnet(1) + avchnet(2) + avchnet(3) + avchnet(4)
+ avchnet(5) + avchnet(6) + avchnet(7) + avchnet(8) + avchnet(9) +
avchnet(10) + avchnet(11) + avchnet(12) + avchnet(13) + avchnet(14) +
avchnet(15) + avchnet(16) + avchnet(17) + avchnet(18) + avchnet(19) +
avchnet(20);
AvTavch = max (avchnet);
end
if (AvTavch < 100)
disp ('Needed Spectrum for Saftey Gaurd Spectrum is = ')
disp (gardspectrum);
disp ('Therefore the remain spectrum is = ');
disp (Specttestsav - gardspectrum)
disp ('The calculation for admitting first CRN is');
disp ('Needed Spectrum for new CRN is = ');
disp (AvTavch);
disp ('Needed Spectrum for CRNs Scalability is = ');
disp (ScalabilityTOT);
disp ('Needed Spectrum for PNs Scalability is = ');
```

```
disp (DeltaOccpancy);
SpectAvailable = Specttestsav - AvTavch - DeltaOccpancy -
ScalabilityTOT;
disp ('Total Needed Spectrum to Accept an operation of new
CRN is = ');
disp (AvTavch + ScalabilityTOT + DeltaOccpancy);
disp ('which must be larger than Available spectrum - Gaurd
Spectrum')
if (SpectAvailable > gardspectrum)
disp (' YES: The available spectrum is enough to Operate
a new CRN');
disp (' ')
N=N+1;
while (SpectAvailable > AvTavch + gardspectrum)
disp ('While Available Spectrum is larger than
needed spectrum for new CRN and gaurd spectrum')
disp ('Then another CRN will be accepted to
operate')
SpectAvailable = SpectAvailable - AvTavch;
N=N+1;
end
disp ('Maximum allowed CRNs are=');
disp(N);
else disp ('No: The available spectrum is not enough to
Operate a new CRN'); NO = NO+1; disp (' ')
end
Z = Z+ N;
else disp ('Total of average utilised spectrum by')
disp ('the existing networks is more than 100% ')
end
end
if (Tavch < 100)
disp ('Accepted times are')
ACC= Comp - NO;
disp (ACC)
disp ('of')
disp (Comp)
if ACC < Comp
disp ('There is a chance to do not giving permission to the
new CRN with ')
disp ((NO/Comp)* 100)
disp ('So the Average Allowed CRNs will stay')
disp (Nomore)
else AvZ = Z / Comp;
disp ('Average of Allowed Numbers are')
disp (AvZ)
end
else disp('Please repeat the measurements with')
disp ('correct constraints for the existing CRNs utilising')
end
clear
```

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